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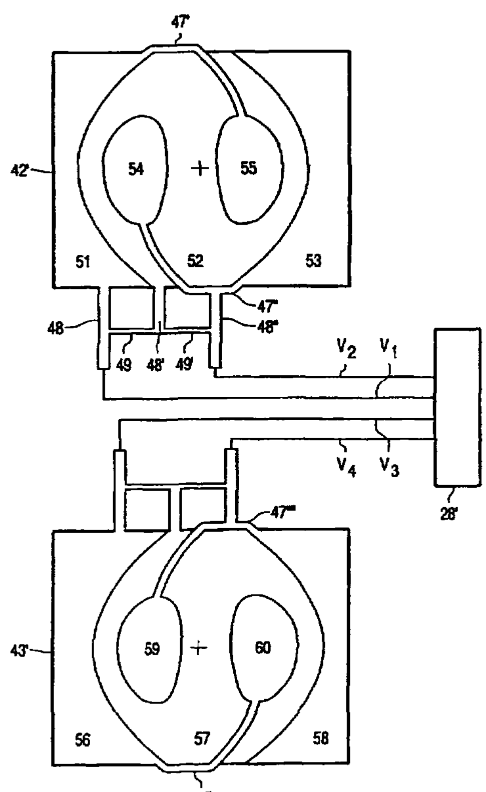

(57) Abstract: An optical wavefront modifier (27) is adapted for modifying a wavefront of an optical beam passing through the modifier. The modifier comprises a first and a second transparent electrode layer (42', 43') and a flat medium (46) for modifying the wavefront in dependence on electrical excitation and arranged between the electrode layers. The first electrode layer (42') comprises three or more electrodes (51-55) of a transparent, conductive material. The electrode layer also comprises a series arrangement of resistors, comprising three terminals (48, 48', 48") connected to the electrodes and resistors (49, 49') connecting the terminals. The resistors are made of the same transparent conductive material as the electrodes.

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Optical wavefront modifier

The invention relates to an optical wavefront modifier for modifying a wavefront of an optical beam passing through the modifier, the modifier comprising a first and a second transparent electrode layer and a medium for modifying the wavefront in dependence on electrical excitation of the medium and arranged between the electrode layers, the first electrode layer comprising three or more electrodes of a transparent, conductive material.

An optical wavefront modifier may be used to change the properties of an optical beam, for instance changing its vergence by introducing a focus curvature in the wavefront of the beam or changing the direction of the beam by introducing tilt. A wavefront modifier may also operate as a wavefront compensator for compensating an undesired shape of the wavefront of an optical beam, e.g. for removing spherical aberration or coma from a wavefront.

European Patent Application No. 0 745 980 shows an optical scanning head using an optical wavefront modifier as wavefront compensator for compensating coma. The compensator uses an electrostriction medium arranged in the optical path between the radiation source and the objective system. One of the electrode layers of the compensator comprises three electrodes of a transparent material, each of the electrodes being electrically connected to a control circuit. A disadvantage of the known modifier is the relatively large number of electrical connections to be made between the modifier and the control circuit.

It is an object of the invention to provide a modifier that requires a reduced number of electrical connections for its control.

This object is achieved if, according to the invention, the first electrode layer comprises a series arrangement of resistors, the electrodes being electrically connected to the series arrangement of resistors and the resistors being made of said transparent, conductive material. The invention is based on the recognition, that the voltages used for controlling the separate electrodes of the modifier have such a mutual dependence, that the voltages can be derived from a series arrangement of resistors. When this series arrangement of resistors is integrated in an electrode layer of the modifier, the only voltages to be applied to the modifier are the voltages to be connected to the terminals of the series arrangement, thereby

reducing the number of electrical connections to the modifier. The number of terminals in a configuration is two for simple electrode configurations and may be three or more for more elaborate configurations. The integration of the series arrangement in the electrode layer also simplifies the manufacture of the modifier.

Preferably, the series arrangement comprises three terminals for supplying control voltages to the series arrangement. This allows a division of the electrodes in the configuration in two groups, each group being controlled independently of the other group.

The electrodes have preferably a configuration for imparting a wavefront modification in Seidel form. In the Seidel form the electrodes extend from one side of the cross-section of the optical beam to the other side for most optical aberrations, allowing an easy connection to the series arrangement of resistors. In contrast, wavefronts in Zernike form require in general electrode shapes where one electrode is completely surrounded by another electrode; an electrical connection to the surrounded electrode must be made by a small strip through the surrounding electrode, thereby disturbing the electrode pattern.

A further aspect of the invention relates to a device for scanning an optical record carrier having an information layer, comprising a radiation source for generating a radiation beam, an objective system for converging the radiation beam through the transparent layer to a focus on the information layer, and a detection system for intercepting radiation from the record carrier, wherein an optical wavefront modifier is arranged in the optical path between the radiation source and the detection system, which modifier comprises a first and a second transparent electrode layer and a flat medium for modifying the wavefront in dependence on electrical excitation of the medium and arranged between the electrode layers, the first electrode layer comprising three or more electrodes of a transparent, conductive material, and the first electrode layer comprises a series arrangement of resistors, the electrodes being electrically connected to the series arrangement of resistors and the resistors being made of said transparent, conductive material. The modifier is particularly suitable for use in a scanning device. The radiation source, modifier and objective system are generally integrated in an optical head, which moves with respect to the chassis of the scanning device, in which the control circuit is arranged, in order to follow tracks on the record carrier. A reduction of the number of electrical connections between the optical head and the chassis facilitates the movement of the optical head.

The objects, advantages and features of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings, in which

Figure 1 shows a scanning device according to the invention;

Figure 2 shows two laterally displaced comatic wavefront distortions WD and the difference DIFF between them as a function of radial position r in the radiation beam;

Figure 3 shows a cross-section of an aberration compensator in the form of a liquid crystal cell;

Figure 4A shows an electrode configuration for introducing decentred coma;

Figure 4B shows two superposed electrode configurations for introducing decentred coma;

Figure 5 shows electrical connections between the electrode configurations of Figure 4A and a control circuit;

Figures 6A and B6 show two embodiments of a control circuit for the electrode configurations of Figure 4A;

Figure 7 shows an electrode configuration for introducing decentred coma;

Figure 8A shows the value of the control voltages on the electrodes in the configuration of Figure 7;

Figure 8B shows the dependence of the asymmetry factors p_+ and $p\_$ on the displacement of the objective system;

Figures 9 and 10 show a series arrangement of resistors connecting electrodes in an electrode configuration;

Figure 11 shows an electrode configuration for introducing decentred coma and having the series arrangement of resistors integrated in the electrodes;

Figure 12 shows an electrode configuration for introducing centred astigmatism;

Figure 13 shows a control circuit for an aberration compensator having electrode configurations for both coma and astigmatism; and

Figure 14 shows an electrode configuration for introducing spherical aberration.

Figure 1 shows a device for scanning an optical record carrier 1. The record carrier comprises a transparent layer 2, on 1 side of which information layer 3 is arranged.

The side of the information layer facing away from the transparent layer is protected from environmental influences by a protection layer 4. The side of the transparent layer facing the device is called the entrance face 5. The transparent layer 2 acts as a substrate for the record carrier by providing mechanical support for the information layer. Alternatively, the transparent layer may have the sole function of protecting the information layer, while the mechanical support is provided by a layer on the other side of the information layer, for instance by the protection layer 4 or by a further information layer and a transparent layer connected to the information layer 3. Information may be stored in the information layer 3 of the record carrier in the form of optically detectable marks arranged in substantially parallel, concentric or spiral tracks, not indicated in the Figure. The marks may be in any optically readable form, e.g. in the form of pits, or areas with a reflection coefficient or a direction of magnetisation different from their surroundings, or a combination of these forms.

The scanning device comprises a radiation source 6, for example a semiconductor laser, emitting a diverging radiation beam 7. A beam splitter 8, for example a semitransparent plate, reflects the radiation beam towards a collimator lens 9, which converts the diverging beam 7 into a collimated beam 10. The collimated beam 10 is incident on objective system 11. The objective system may comprise one or more lenses and/or a grating. The objective system 11 has an optical axis 12. The objective system 11 changes the collimated beam 10 to a converging beam 13, incident on the entrance face 5 of the record carrier 1. The converging beam 13 forms a spot 14 on the information layer 3. Radiation reflected by the information layer 3 forms a diverging beam 15, transformed into a collimated beam 16 by the objective system 11 and subsequently into a converging beam 17 by the collimator lens 9. The beam splitter 8 separates the forward and reflected beams by transmitting at least part of the converging beam 17 towards a detection system 18. The detection system captures the radiation and converts it into electrical output signals 19. A signal processor 20 converts these output signals to various other signals. One of the signals is an information signal 21, the value of which represents information read from the information layer 3. The information signal is processed by an information processing unit for error correction 86. Other signals from the signal processor 20 are the focus error signal and radial error signal 22. The focus error signal represents the axial difference in height between the spot 14 and the information layer 3. The radial error signal represents the distance in the plane of the information layer 3 between the spot 14 and the centre of a track in the information layer to be followed by the spot. The focus error signal and the radial error signal are fed into a servo circuit 23, which converts these signals to servo control signals 24

for controlling a focus actuator and a radial actuator respectively. The actuators are not shown in the Figure. The focus actuator controls the position of the objective system 11 in the focus direction 25, thereby controlling the actual position of the spot 14 such that it coincides substantially with the plane of the information layer 3. The radial actuator controls the position of the objective lens 11 in a radial direction 26, thereby controlling the radial position of the spot 14 such that it coincides substantially with the central line of track to be followed in the information layer 3. The tracks in the Figure run in a direction perpendicular to the plane of the Figure.

The scanning device of Figure 1 has a relatively large tolerance range for tilt of the optical record carrier 1. It thereto determines the aberration caused by the tilted record carrier in the converging beam 13, and compensates the aberration by introducing a wavefront distortion in the collimated beam 10. The wavefront distortion is introduced by an aberration compensator 27 arranged in the collimated beam 10. A control circuit 28 controls the wavefront distortion via control signals 29. The value of the aberration to be compensated is determined by an aberration detector, which, in this embodiment, is a tilt detector 30. The tilt detector emits a radiation beam 31 towards the optical record carrier 1 and detects the angle of the beam reflected by the record carrier. The position of the spot of the reflected beam is a measure for the angle and, hence, for the tilt of the record carrier. The measured tilt is directly proportional to the coma in the converging beam 13. Hence, the tilt signal 32, i.e. the output signal of the tilt detector 30, can be used directly as input for the control circuit 28, thereby controlling the amount of coma introduced by the aberration compensator 27.

The tilt detector 30 may be of any type. The tilt signal may also be derived from a combination of detector output signals 19. In that case the tilt detector forms part of the control circuit 28.

The wavefront distortion introduced by the aberration compensator 27 will only compensate the aberration introduced by the tilted record carrier if the introduced aberration is correctly centred with respect to the objective system 11. The compensation is not correct anymore, if the introduced aberration is centred on the axis of collimated beam 10 and the objective system is displaced in a radial direction 26 because of radial tracking. The effect of this displacement is shown in Figure 2, giving wavefronts in that radial cross-section of the radiation beam in which the objective system 11 has its radial displacement d. The displacement d is normalised on the radius of the entrance pupil of the objective system. Drawn curve 37 represents a comatic wavefront distortion WD, centred on the optical axis of the radiation beam 10 at r=0 and introduced by the aberration compensator 27. The dashed

line 38 represents the comatic wavefront distortion to be compensated and caused by the tilted optical record carrier 1, and displaced from the optical axis by a distance d due to a displacement of the objective system 11. It is clear from the Figure that, when the displacement d is zero, the introduced aberration 37 will perfectly cancel the aberration 38, thereby providing a spot 14 on the information layer 3 of the record carrier 1 of high quality. When the displacement d is not equal to zero, the wavefronts 37 and 38 will not cancel each other, thus causing an imperfect compensation. The resulting wavefront error DIFF is the difference between curves 37 and 38, shown in Figure 2 as line 39. For small displacements d, the difference 39 is proportional to the derivative of line 37 with respect to the co-ordinate in the direction of the displacement. The resulting wavefront error is one radial order lower than the wavefront WD, and in this case is astigmatism, the value of which is proportional to the displacement d and the amount of coma to be compensated. This astigmatism must also be compensated by the aberration compensator 27. A more detailed analysis of the wavefront errors shows, that a decentred comatic wavefront not only introduces astigmatism but also a small amount of wavefront tilt and defocus. The wavefront tilt and defocus will be corrected automatically by the radial and focus servo respectively.

The measurement of the position of the objective system 11 in the radial direction 26, required as input for the aberration compensation, is performed by a position detector 33 as shown in Figure 1. A position signal 34 generated by the position detector is used as input for the control circuit 28. The position of the objective system 11 may be measured using any known position measuring method. An optical method is preferred, because it does not affect the mechanical properties of the objective system. The position may also be derived from the detector output signals 19, as is known inter alia from U.S. Patent 5,173,598 (PHN 13695). In that case the position detector forms a part of the signal processor 20.

Figure 3 shows an embodiment of the aberration compensator, in the form of a liquid crystal cell. The cell comprises two plane parallel transparent plates 40 en 41, made of for instance glass. On the inner sides of the transparent plates transparent electrode layers 42 and 43 are arranged. The inner sides of the electrode layers are covered with alignment layers 44 and 45 respectively. A nematic liquid crystal material 46 is arranged between the two alignment layers. The liquid crystal material may be replaced by a ferro-electric medium, when higher switching speeds are required. The electrode layer comprises transparent conductors, made of for instance indium tin oxide. The refractive index of the liquid crystal material is controlled by the voltage difference between the electrode layers 42 and 43. Since

the refractive index determines the optical path length through the liquid crystal layer 46, a temporal and/or spatial variation of the voltage difference can be used to change the wavefront of a radiation beam passing through the aberration compensator. Although the Figure shows a medium in the form of a flat liquid crystal layer, the medium may be curved. The thickness of the medium may vary as a function of position in the cross-section of the radiation beam, thereby reducing the requirements imposed on the control voltages.

Figure 4A shows the electrode structures in electrode layer 42 and 43. These electrode structures are adapted to introduce off-centre coma in the radiation beam. The electrode structures comprise various electrodes in the form of electrically conducting transparent regions separated by small non-conducting intermediate regions, not shown in the Figure. The electrode layer 42 comprises electrodes 51 to 55. Similarly, the electrode layer 43 comprises electrodes 56 to 60. The Figure shows a plan view of the electrode layers 42 and 43. The intersection of the optical axis 35 of collimated beam 10 with the electrode layers is indicated by the cross 50. The electrode structure is adapted to introduce a comatic wave front aberration in the radiation beam passing through the liquid crystal cell in the form of the Zernike polynomial $(3r^3 - 2r) \cos \theta$, where r-θ are the polar co-ordinates in the cross-section of the radiation beam. The angle θ is zero along the horizontal direction in the Figure, from the cross 50 towards electrode 54. The width and position of electrode 54 is indicated by the dot and dash line 36 in Figure 2. The width is chosen such that the electrode 54 covers those regions of the aberration compensator where the value of the Zernike polynomial $(3r^3 - 2r) \cos \theta$ is larger than a predetermined value 'a'. In practice, 'a' has a value between 0.1 and 0.35, and preferably has a value approximately equal to 0.25. The same applies to the other electrodes. The electrode structure in layer 42 is offset in the left direction with respect to the centre 50. The electrode structure in the electrode layer 43 is offset to the right with respect to the centre 50. The amount of offset is determined by the maximum displacement of the objective system 11. Figure 4B shows a plan view of both electrode layers 42 and 43 superposed. The offset of the electrode structures is in the radial direction 26 as indicated in Figure 1.

Figure 5 shows a plan view of electrode layers 42' and 43', which have an electrode configuration similar to the electrode layers 42 and 43, respectively, but with additional electrical connections between the separate electrodes. The electrodes 51 and 55 are electrically connected by a narrow strip electrode 47'. The width of the strip electrode should be sufficiently small so as not to affect the operation of electrode 52; on the other hand, the width should be large enough to avoid reduction of the switching time of the

aberration compensator. Likewise, electrodes 53 and 54, 56 and 60, 58 and 59 are pairwise electrically connected by strip electrodes 47", 47'" and 47"", respectively. The three voltages required for the control of the electrodes in electrode layer 42' are applied by means of three terminals 48, 48' and 48". The end terminals 48 and 48" are connected to the central terminal 48' by means of two narrow strip electrodes 49 and 49', respectively. The strip electrodes 49 and 49' form resistors, which, together with the terminals, form a series arrangement of resistors. The control circuit 28' provides the control signals 29, four of which are indicated in Figure 5 by V_1, V_2, V_3 and V_4. Control signal V_1 is applied to terminal 48 and V_2 to terminal 48". Since the resistance value of electrodes 49 and 49' is chosen to be equal, the voltage at terminal 48' is the average of the voltages on terminals 48 and 48". Control signals V_3 and V_4 are applied to a series arrangement of resistors on electrode layer 43', the series arrangement being similar to that on electrode layer 42'.

The aberration compensator 27 may be controlled by applying various DC voltages to its electrodes. However, it is preferred to use AC voltages for the control in view of the stable operation of the liquid crystal. Figure 6A stable operation shows an embodiment of the control circuit 28, providing AC control voltages for the electrodes in the layout shown in Figure 5. The tilt signal 32 is used as input for a voltage to voltage converter 61, which provides at its output a first control signal 62, having a value ΔV, dependent on the tilt signal 32. The first control signal 62 is connected to an adder 63. A voltage source 63' provides a reference voltage V_0 to the adder 63. The adder has two output signals D_1 and D_2, the values of which are $V_0 + \Delta V$ and $V_0 - \Delta V$, respectively. The two output signals D_1 and D_2 are used as input for a multiplier 64. A square-wave generator 64' provides a square wave signal, having a fixed amplitude and a predetermined frequency, preferably lying in the range between 1 and 10 kHz. This square-wave signal is used as input for the multiplier 64. The multiplier provides two AC control voltages A_1 and A_2 as output signals. Each of the two output signals has a square-wave form and a zero average value. The peak-peak amplitude of signal A_1 is equal to $V_0 + \Delta V$, that of signal A_2 is equal to $V_0 - \Delta V$. The sign and magnitude of the control signals A_1 and A_2 are such, that, when applied to the aberration compensator 27, the correct amount of coma is introduced in the collimated beam 10 to compensate the coma caused by the amount of tilt of the optical carrier 1 as represented by the tilt signal 32. Thereto, the value ΔV is proportional to the value of the tilt signal. The control signals A_1 and A_2 are connected to four change-over switches 65, which have the signals V_1 to V_4 as output signals. The four output signals V_1 to V_4 can be switched between the control signal A_1 or A_2 and ground. The switches 65 are controlled by a switch control circuit 66, which has

the position signal 34 as input. When the position signal is positive, the four switches 65 are in the positions as shown in Figure 6A. When the position signal is negative, the four switches are in their other positions. Hence, in the drawn position of the switches, the electrodes 56-60 are all connected to the ground, and varying voltages are applied to the electrodes 51 to 55. The voltage applied to electrodes 51 and 55 is $V_0 + \Delta V$, to electrodes 53 and 54 $V_0 - \Delta V$, and to electrode 52 via the series arrangement V_0. The voltages are such that a comatic wavefront aberration is introduced which is offset to the left hand side in Figure 5 with respect to the optical axis 35. When the sign of the position signal 34 reverses, the electrodes 51 to 55 are connected to the ground, and the varying voltages are applied to the electrodes 56 to 60. The resulting comatic wavefront aberration is offset to the right hand side with respect to axis 35. The value of the predetermined voltage V_0 depends on the properties of the aberration compensator 27, in particular the liquid crystal material, and is chosen such that the response of the compensator is proportional to ΔV.

Figure 6B shows an alternative embodiment of the control circuit 28. The tilt signal 32 is used as input for a voltage-to-voltage converter 161, which provides at its output a first control signal having a value $\frac{1}{2}\Delta V$, proportional to the amount of tilt. The tilt signal 32 and the position signal 34 are used as input for a multiplier 160, which provides at its output a second control signal having a value of $\frac{1}{2}(x/x_0)\Delta V$, where x is proportional to the displacement of the objective system and x_0 is the maximum displacement of the objective system. The first and second control signal are fed into an adder 162, forming two output signals $\Delta V_1 = \frac{1}{2}\Delta V - \frac{1}{2}(x/x_0)\Delta V$ and $\Delta V_2 = \frac{1}{2}\Delta V + \frac{1}{2}(x/x_0)\Delta V$. A voltage source 165 provides a reference voltage V_0 to an adder 163. The adder also has the signals ΔV_1 and ΔV_2 as inputs and forms four signals having the values $V_0 - \Delta V_1$, $V_0 + \Delta V_1$, $V_0 - \Delta V_2$ and $V_0 + \Delta V_2$. A square-wave generator 166 provides a square wave signal, having a fixed amplitude and a predetermined frequency, preferably lying in the range between 1 and 10 kHz. The square wave signal and the five signals are used as input for a multiplier 164. The multiplier provides six AC control signals V_1 to V_4, which are connected to the aberration compensator 27. Each of the AC control signals has a square-wave form and a zero average value. The peak-peak amplitude of the signals V_1 to V_4 is $V_0 - \Delta V_1$, $V_0 + \Delta V1$, $V_0 - \Delta V_2$ and $V_0 + \Delta V_2$, respectively. The signals V_1 and V_2 have the same phase; likewise V_3 and V_4. The two groups of signals may have the same phase or may be mutually 180° out of phase. The amplitudes of V_0, ΔV_1 and ΔV_2 depend on the properties or the aberration compensator and

the phase between the groups of signals, and are chosen such that the response of the compensator is proportional to ΔV_1 and ΔV_2.

A proper balancing of aberrations in this embodiment of the aberration compensator requires that the displacement between the two electrode structures in the electrode layers 42 and 43 is equal to approximately half the maximum peak-peak displacement of the objective system 11. If the maximum peak-peak displacement of the objective system is e.g. from –400 to +400 μm, the displacement between the electrode structures is preferably 400 μm.

The match between the wavefront aberration introduced by the aberration compensator 27 and the Zernike polynomial for coma may be improved by increasing the number of electrodes in the electrode layers 42 and 43. Figure 7 shows an electrode configuration that can be used in the aberration compensator 27. The electrodes form a series of small strips with a small spacing, causing a smooth transition of the refractive index of the liquid crystal material under one electrode to the refractive index of the liquid crystal material under the neighbouring electrode. The reduction of the phase changes between electrodes reduces the higher order aberrations, even when the objective system 11 is positioned off-centre. The particular width of the electrodes of the embodiment, decreasing with increasing radius, as shown in Figure 7 allows the electrodes to be controlled with a voltage that increases linearly with the strip of the electrode. If the 2N+1 strips are numbered consecutively with an index running as –N, -N+1, ...0,1, ...N, then the strip with index j covers that area in the (x,y) plane that comply with

$$\frac{2j-1}{2N+1} \langle \; W_{31}(x,y) \; \langle \; \frac{2j+1}{2N+1}$$

$W_{31}(x,y) = (x^2+y^2)x$ is the Seidel polynomial for coma, and x,y are normalised co-ordinates in the cross-section of the radiation beam in the plane of the aberration compensator, where x is in the direction of displacement of the objective system. This electrode structure introduces a comatic wavefront aberration in the beam passing through the aberration compensator. The aberration is not of the Zernike type but of the Seidel type, which has the advantage of a simpler layout of the electrodes, each electrode having a connection outside the cross-section of the beam, and a simple scheme for the control voltages. The tilt and defocus, which are inherently introduced into the radiation beam 10 when using Seidel aberrations, will be compensated automatically by the focus and radial tracking servo of the device.

The electrode configuration 67 shown in Figure 7 may be used in both electrode layers 42 and 43, and displaced with respect to one another as indicated in Figure 4B. The control of the voltages of the electrodes in the two electrode layers can be carried out by a control circuit similar to the ones shown in Figure 6A and B. In an alternative embodiment, the electrode configuration 67 is arranged in electrode layer 42 and centred on the optical axis 35. The electrode layer 43 comprises a single electrode covering the entire cross-section of the radiation beam 10 and set at a fixed potential. When controlled by a voltage that increases linearly from one electrode to the next, the electrode configuration will give rise to centred comatic wavefront aberration. The astigmatism, required when the objective system 11 is off-centre, can be introduced by an asymmetric control of the electrodes as indicated in Figure 8. Figure 8 shows the voltage as a function of the electrode number, where electrode number zero is the central electrode of the electrode configuration, which is set at a voltage V_0. The drawn line 68 indicates the linearly increasing voltage for the generation of centred coma. The dashed line 69 indicates the voltages for simultaneously generating coma and astigmatism.

The electrode configuration 67 as shown in Figure 7 requires a relatively large number of voltages to be generated by the control circuit 28. The number of voltages to be generated by the control circuit can be reduced, if the electrode configuration is provided with a series arrangement of resistors that forms the required voltages. Figure 7 shows a series arrangement made up of resistors 70, the arrangement being provided with a central terminal 71 and two end-terminals 72 and 73. The three terminals 71, 72 and 73 allow both a control by a linear voltage indicated by drawn line 68 and by a voltage indicated by dashed line 69 in Figure 8A. A more accurate control can be obtained if the number of terminals is increased. The voltages applied to end terminals 72 and 73 may be chosen asymmetrical with respect to the voltage V_0 on the central terminal 71. The voltage Vj on strip j can then be written as

$$V_j = V_0 - p_{\pm} \frac{j}{N} \Delta V ,$$

where ΔV is equal to $(V_{+N} - V_{-N})/2N$ if there is no displacement of the objective system. The asymmetry factor p_+ is used for $j \geq 0$ and p_- for $j<o$ for one sign of the tilt signal; p_- is used for $j \geq 0$ and p_+ for $j<0$ for the other sign of the tilt signal. The values of the factors depend on the displacement d as indicated in Figure 8B, where the drawn line represents the values of p_+ and the dashed line those of p_-.

Figure 9 shows an electrode configuration wherein the series arrangement of resistors is integrated in the conductive layer of the electrode layer. The embodiment has five electrodes 76-80 separated by small non-conductive strips. The three terminals 81, 82 and 83 are connected by four resistors 84, formed by strips of conductive layer, connected in series between the terminals. A high resistance can be obtained by decreasing the width of the strips that make up the resistors 84. Five taps 85 connect the resistors with the electrodes.

Figure 10 shows an alternative embodiment of the electrode configuration of the aberration compensator 27. The configuration comprises a structure 88 for generation of coma, similar to the structure shown in Figure 7. The individual strips of the structure 88 are connected by taps in the form of strips 89 to a resistor maze 90. The maze forms resistors of equal value between subsequent taps 89. The control voltages are applied to the configuration through terminals 91, 92 and 93. The extent of the maze may be reduced by arranging these strips of the maze in a zigzag structure. Alternatively, the strips of the maze may be arranged around the structure 88.

Figure 11 shows an embodiment 67' of the electrode configuration of the aberration compensator 27 similar to the embodiment shown in Figure 7. The series arrangement of resistors has been integrated in the transparent electrodes. Neighbouring electrodes 79' and 80' are connected by a small strip 81' acting as resistor, made of the same material as the electrodes and running substantially parallel to the non-conducting intermediate region 82' separating the electrodes. This arrangement of the resistors has the advantage, that the electrode structure can be kept relatively small, because the resistors do not require any space in the structure outside the cross-section of the radiation beam. Moreover, the resistors give only a relatively small disturbance of the electrical field pattern generated by the electrodes. The voltages on the three terminals 71', 72' and 73', connected to the central electrode and the two outer electrodes, respectively, can be controlled in the same way as the voltages on the terminals 71, 72 and 73 in Figure 7.

The resistor of the elements in the maze must be sufficiently large to ensure a tolerable low level of dissipations and sufficiently small to ensure an RC-time of the cell that is much smaller than the period of the AC-voltage.

The coma caused by tilt of the record carrier 1 may also be compensated by an aberration compensator that introduces centred coma and centred astigmatism. Thereto, the aberration compensator 27 is provided with electrode layer 42 having an electrode configuration for introducing centred coma, and electrode layer 43 having an electrode configuration for introducing centred astigmatism. The electrode configuration for centred

coma is similar to the electrode configuration 42 shown in Figure 4A but centred on the intersection 50 of optical axis 35. The centred coma may also be introduced by the electrode configuration 67 shown in figure 7.

Figure 12 shows an electrode configuration 95 in electrode layer 43 for introducing centred astigmatism. The electrode pattern is centred on the optical axis 35. A circle 96 in the electrode configuration indicates the cross-section of the radiation beam in the plane of the configuration. The electrodes in both electrode layers may be confined to the area within the beam cross-section 96, or may extend outside the beam cross- section. The configuration 95 is adapted to introduce astigmatism in the Zernike form, which can be described as $Z_{22} = x^2-y^2$. The normalised co-ordinates x,y are indicated in the Figure. This Zernike form for astigmatism is particularly suitable for an aberration compensator which also introduces coma in the Seidel form. In its simplest form, the electrode configuration comprises a central electrode 97 and four side electrodes 98-101. The position of the border between the electrodes and the control voltages is determined as follows. The points in the configuration with $Z_{22}(x,y) > a$ are set at a voltage $V_{10} = V_0' - \Delta V$. The points in the configuration with $-a < Z_{22}(x,y) < a$ are set at a voltage $V_{11} = V_0'$. The points in the configuration with $Z_{22}(x,y) < -a$ are set at a voltage $V_{12} = V_0' + \Delta V$. The voltage ΔV is proportional to the amount of astigmatism to be introduced. The value of the parameter a is preferably in the range from 0.10 to 0.60, and, more preferably, substantially equal to 0.25. The electrode configuration shown in Figure 12 is based on a = 0.25.

Figure 13 shows a control circuit for the electrical control of an aberration compensator having both the electrode configuration 67 for introducing coma in the radiation beam passing through the compensator and the electrode configuration 95 for introducing astigmatism in the beam. The control circuit can also be used if the electrode configurations have both a Zernike layout or both a Seidel layout. The control of the coma configuration 67 is similar to the control shown in Figure 6A and B. Hence, voltage converter 105, first control signal 106, adder 107 and voltage source 108 are similar to the corresponding elements 61 to 64' in Figure 6A. The DC output signals D_4, D_5 and D_6 of adder 107 correspond to the output signals D_1, D_2 and D_3, respectively as shown in Figure 6A. The control of the astigmatism configuration 95 uses the tilt signal 32 and the position 34 as input signals. A multiplier 109 forms the product of the two signals. The product is a measure for the astigmatism introduced into the radiation beam by the combination of a centred comatic aberration introduced by the wavefront compensator 27 and a displaced objective system 11. The product is output as a second control signal 110 and used as input for an adder 111. A

voltage source 112 supplies a voltage V_0' to the adder. The adder has three DC output signals D_7, D_8 and D_9, having the values $V_0'+\Delta V$, V_0', $V_0'-\Delta V$ respectively, where ΔV is the value of the second control signal 110. The DC output signals D_4 to D_9 are connected to a multiplier 113, which forms output signals V_7 to V_{12}. A square–wave generator 114, similar to the square-wave generator 64' in Figure 6A, supplies a square wave signal to the multiplier 113. The multiplier 113 multiplies each of the six input signals D_4 to D_9 with the square-wave signal, resulting in six square wave output signals V_7 to V_{12}, respectively, having the wave form of the output of the square-wave generator 114 and an amplitude corresponding to the signals D_4 to D_9. The output signals V_7, V_8 and V_9 are similar to the output signals A_1, A_2 and A_3, respectively, in Figure 6A, and are connected to the terminals 71, 72 and 73, respectively, of the electrode configuration 67 shown in Figure 7. The output voltage V_{10} is connected to side electrodes 98 and 100 of electrode configuration 95 shown Figure 12. The output voltage V_{11} is connected to the central electrode 97, and the output voltage V_{12} is connected to the side electrodes 99 and 101.

The electrode configuration 95 shown in Figure 12 may also be provided with a series arrangement of resistors similar to the series arrangements shown in Figure 5. The side electrodes 99 and 100 are each connected to an end terminal, whereas the central electrode 97 is connected to a central terminal. Electrodes 98 and 100 are connected by a conducting strip, not shown in the Figure; similarly, the electrodes 99 and 101 are connected. The series arrangement of resistors is formed by two narrow electrode strips acting as resistors between the central terminal and each of the end terminals. This configuration does not require the control voltages V_8 and V_{11} of control circuit 113 shown in Figure 13.

The aberration compensator 27 in the above described embodiments compensates coma caused by tilt of the record carrier 1, taking into account the position of the objective system 11. The position of the objective system can also be taken into account for compensators that introduce aberrations other than coma, for instance spherical aberration, caused for instance by variations in the thickness of the transparent layer 2 of the record carrier one. When an optical beam in which centred spherical aberration has been introduced passes through a displaced objective system, the beam after passage through the objective system will suffer from coma which is linear in the displacement and astigmatism which is quadratic in the displacement of the objective system. The compensation of the spherical aberration can be corrected for the displacement of the objective system in a way similar to the correction in the above described embodiments of the aberration compensator. A first adapted embodiment of the aberration compensator comprises a first electrode layer

having an electrode configuration for generating spherical aberration as shown in Figure 14, the centre of which is displaced with respect to the intersection of the optical axis 35 with the electrode layer, and a second electrode layer having a similar electrode configuration for generating spherical aberration, but displaced in a direction opposite to the configuration in the first electrode layer. A second embodiment of the aberration compensator comprises a first electrode layer having an electrode configuration for generating a centred spherical aberration, and a second electrode layer having an electrode configuration for generating centred coma. The two electrode configurations may also be combined into a single electrode layer. A third embodiment of the aberration compensator comprises three electrode layers and two liquid crystal layers between them. One layer is provided with an electrode configuration for generating centred spherical aberration. A second layer is provided with a configuration for generating centred coma and a third layer with a configuration for generating centred astigmatism. The aberration compensator is controlled by the position signal 34 representing the position of the objective system and a signal representing the amount spherical aberration in the radiation beam returning from the record carrier. A sensor for measuring the spherical aberration in the radiation beam is described in the European Application having filing number 98204477.8 (PHN 17.266).

Figure 14 shows a electrode configuration 116 for generating spherical aberration. The Zernike representation of the aberration is $Z_{40} = 6(x^2+y^2)(x^2+y^2-1)+1$. The borders between the electrodes and the voltages applied to them can be derived as follows. The points in the configuration with $Z_{40}(x,y) > a$, i.e. the central area 117 and the ring 121, are set at a voltage $V_0-\Delta V$. The points in the configuration complying with $-a < Z_{40}(x,y) < a$, i.e. the rings 118 and 120, are set at a voltage V_0. The points in the pupil with $Z_{40}(x,y) < -a$, i.e. the ring 119, are set at a voltage $V_0+\Delta V$. The parameter 'a' is preferably in the range from 0.20 to 0.70. The electrode configuration shown in Figure 14 is for $a = \sqrt{3}/4 = 0.433$. This value of a gives equal surface areas for the electrodes to which a voltage $V_0-\Delta V$ is applied and those to which $V_0+\Delta V$ is applied. The electrode configuration for generating spherical aberration may be simplified by forming three concentric rings and applying different voltages to them.

The electrode configurations for generating spherical aberration, coma and/or astigmatism may be combined into a single electrode configuration by a suitable division of the electrode layer into separate electrodes and a corresponding adaptation of the control circuit. The aberration compensator may comprise one electrode layer for introducing two

aberrations, e.g. coma and astigmatism, and one electrode layer for introducing another aberration, e.g. spherical aberration.

Although the above described embodiments of the invention relate to aberration compensators, it will be clear the invention is not limited to these embodiments. The invention can be used in any wavefront modifier, irrespective of correction for transverse displacement of the objective system. The wavefront modifier according to the invention is not limited to wavefront compensators, but include any optical element comprising transparent electrode layers and a medium for modifying the wavefront in dependence on electrical excitation of the medium. An example is a wavefront modifier that introduces a wavefront distortion on the radiation beam that is quadratic in the radius of the wavefront. Such a modifier can be used in a scanning device, wherein an objective system provides for slow and large axial movement of the focus point and the wavefront modifier provides for fast and small axial changes of the focus point. Similarly, the wavefront modifier may introduce tilt in the radiation beam, allowing small displacements of the focus point in a direction perpendicular to the track to be followed by the focus point. This fine movement can be in addition to a coarse movement obtained by a displacement of the objective lens or of the complete optical head.

CLAIMS:

1. An optical wavefront modifier for modifying a wavefront of an optical beam passing through the modifier, the modifier comprising a first and a second transparent electrode layer and a medium for modifying the wavefront in dependence on electrical excitation of the medium and arranged between the electrode layers, the first electrode layer comprising three or more electrodes of a transparent, conductive material, characterized in that the first electrode layer comprises a series arrangement of resistors, the electrodes being electrically connected to the series arrangement of resistors and the resistors being made of said transparent, conductive material.

2. Optical wavefront modifier according to Claim 1, wherein the electrode layer comprises three terminals, which are electrically connected to the series arrangement of resistors.

3. Optical wavefront modifier according to Claim 1, wherein the electrodes have a configuration for imparting a wavefront modification in Seidel form.

4. Optical wavefront modifier according to Claim 1, wherein the series arrangement of resistors is integrated in the electrodes.

5. A device for scanning an optical record carrier having an information layer, comprising a radiation source for generating a radiation beam, an objective system for converging the radiation beam through the transparent layer to a focus on the information layer, and a detection system for intercepting radiation from the record carrier, characterized in that an optical wavefront modifier according to any of the preceding Claims is arranged in the optical path between the radiation source and the detection system.

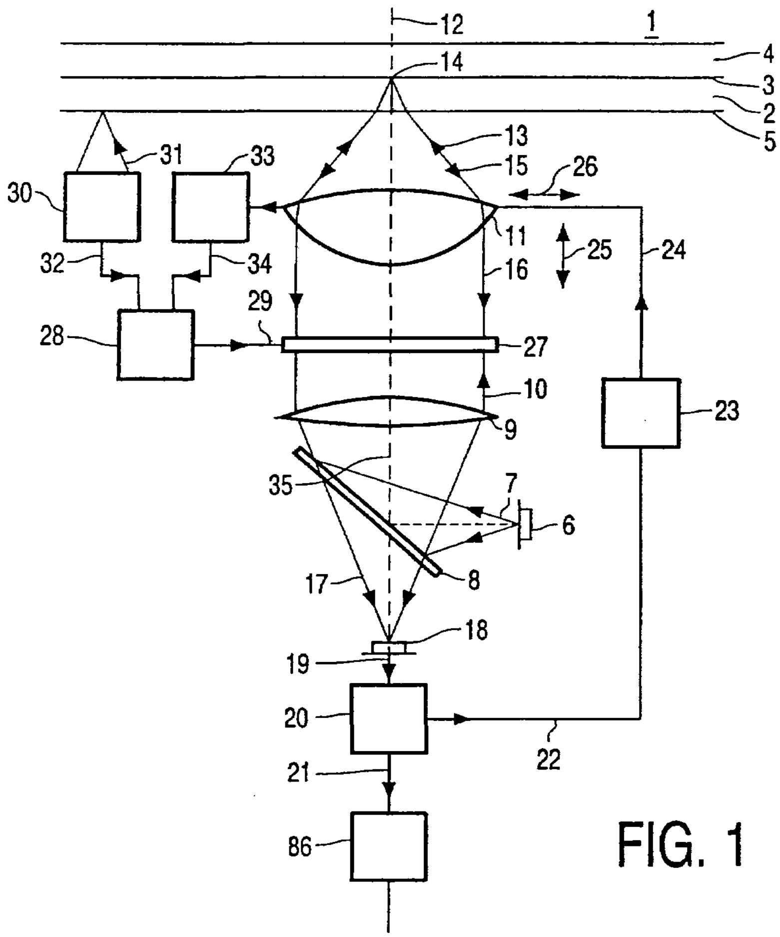

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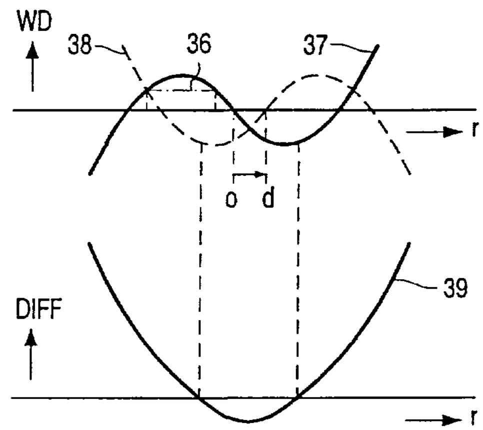
FIG. 1



WD
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DIFF
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FIG. 2

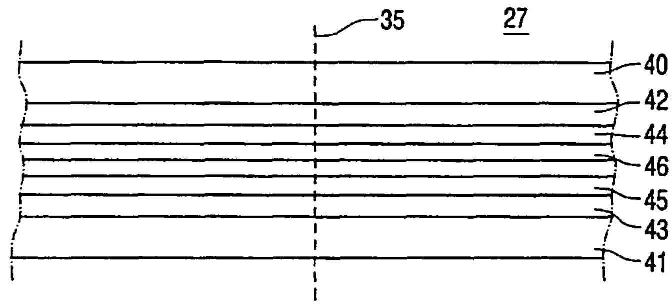


FIG. 3

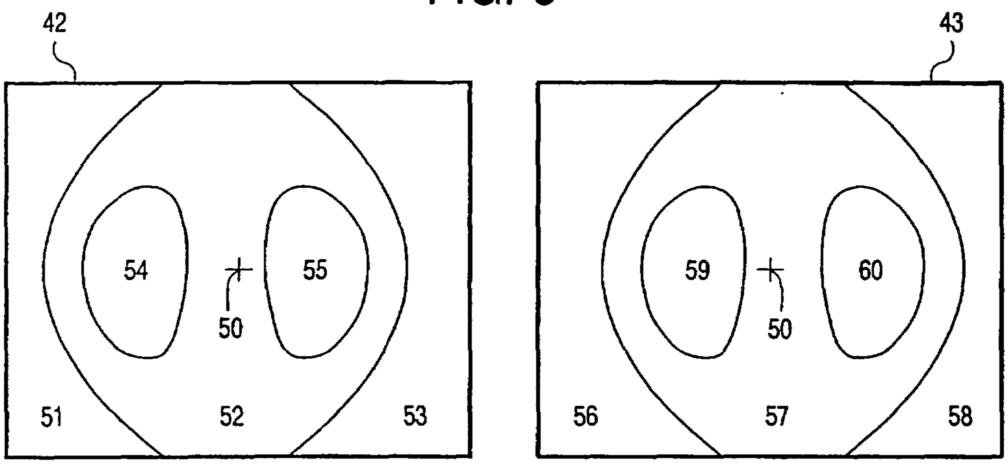


FIG. 4A

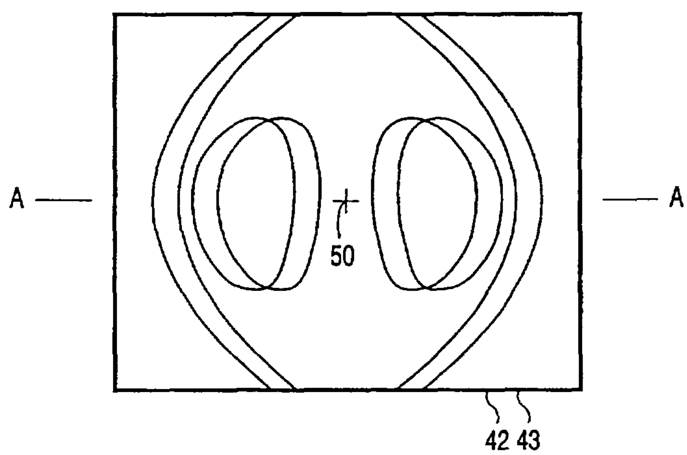


FIG. 4B

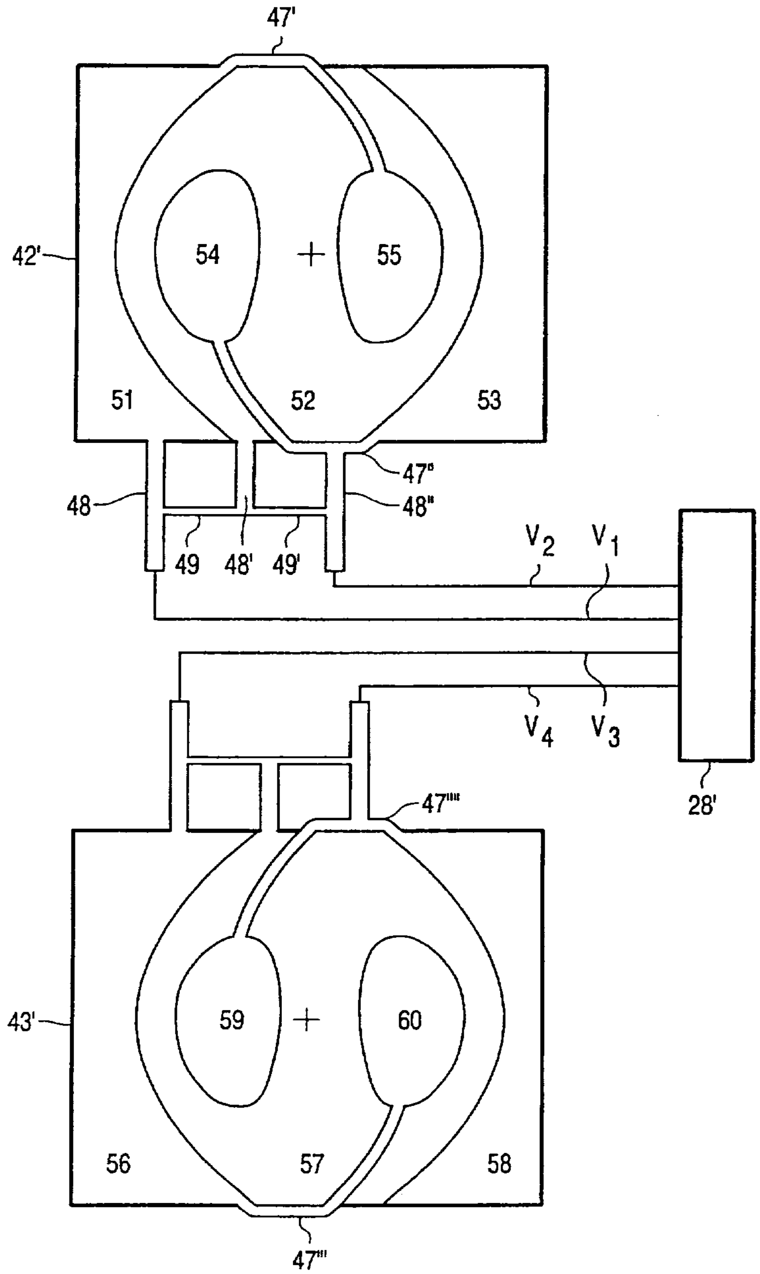
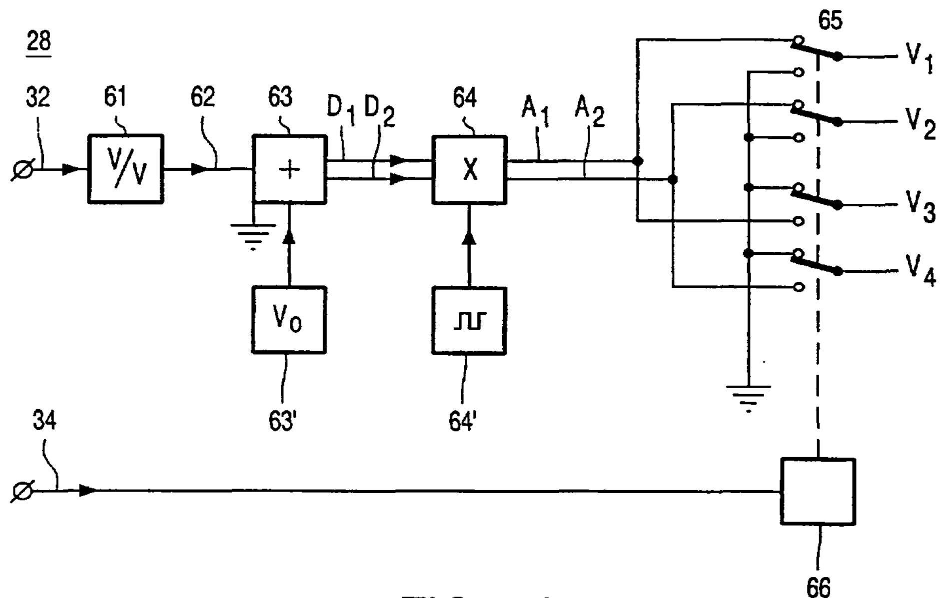
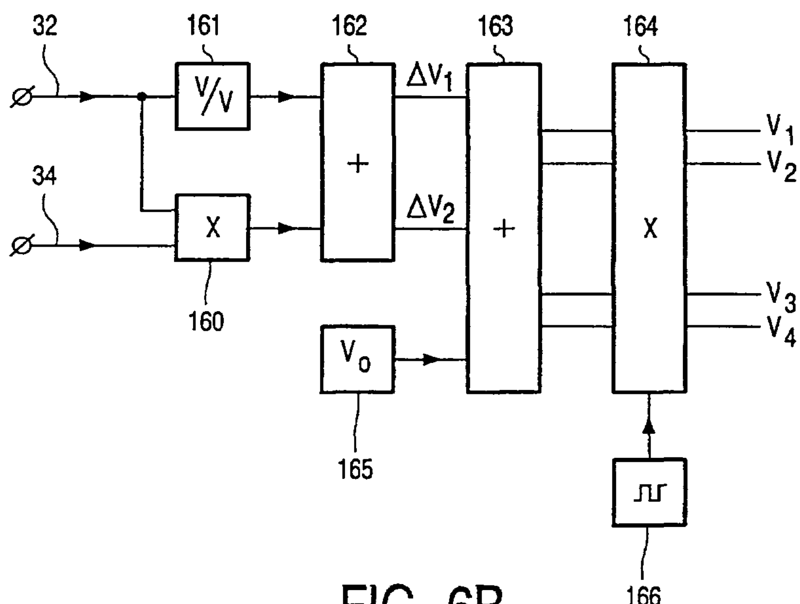

47'
42'
54
55
51
52
53
47"
48
48"
49
48'
49'
V_2
V_1
V_4
V_3
28'
47''''
43'
59
60
56
57
58
47'''

FIG. 5



28
32
61
62
63
D1 D2
64
A1 A2
65
V/V
+
X
V1
V2
V3
V4
V0
63'
64'
34
66

FIG. 6A



32
161
162
163
164
V/V
ΔV1
+
ΔV2
+
X
V1
V2
V3
V4
34
X
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V0
165
166

FIG. 6B

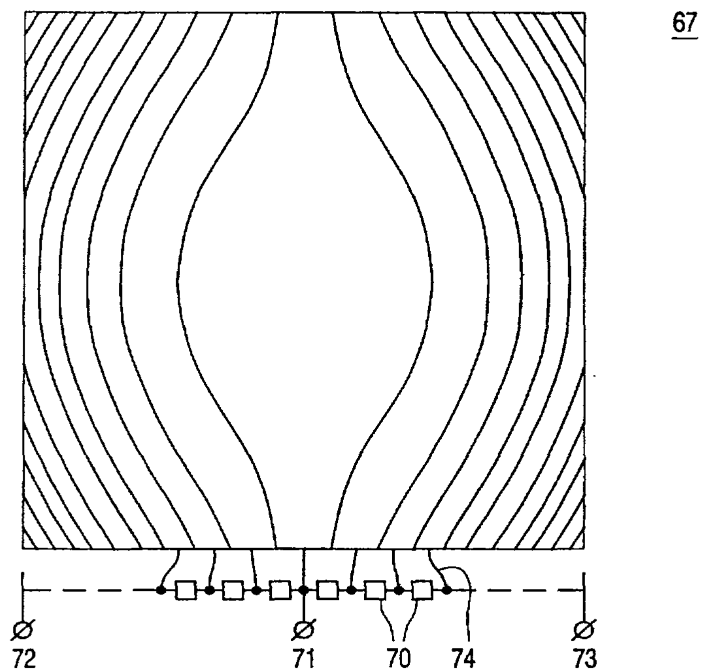


FIG. 7

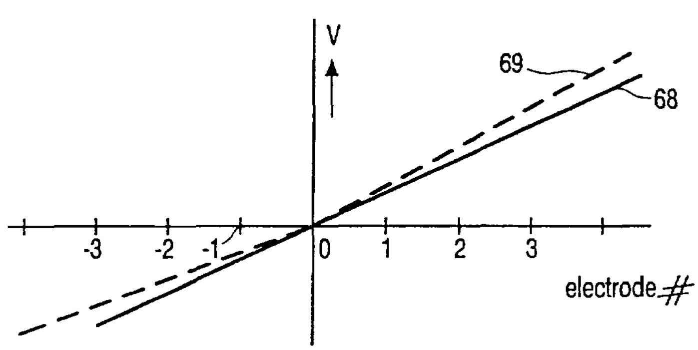


FIG. 8A

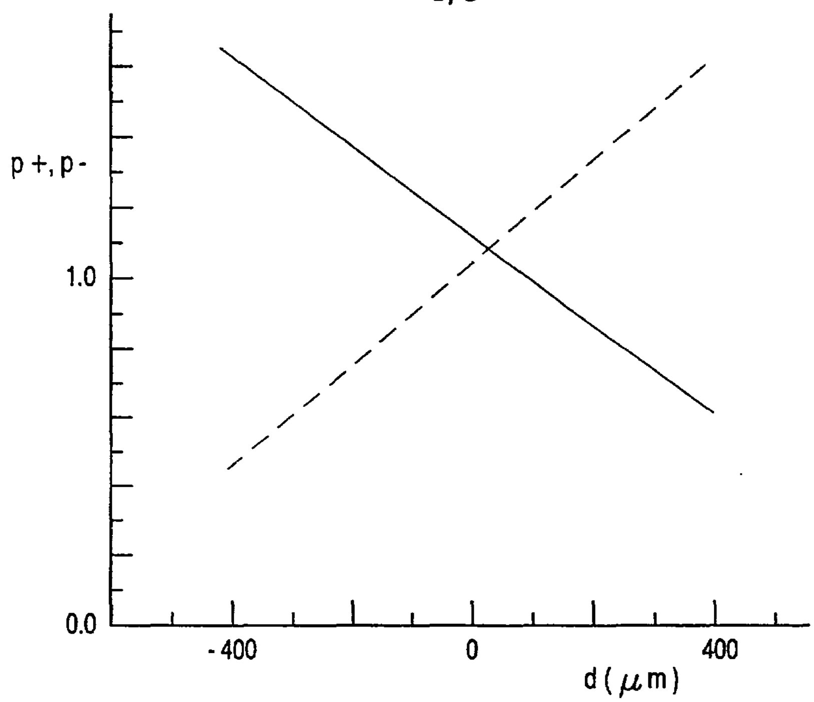


FIG. 8B

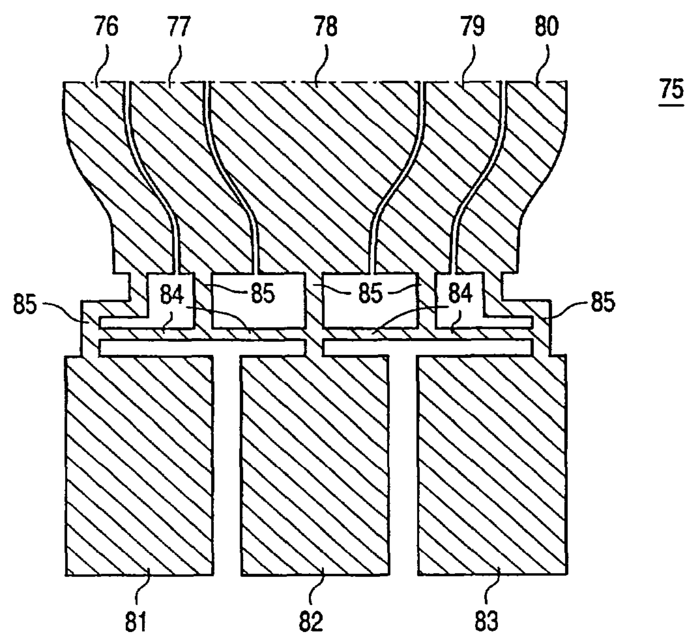


FIG. 9

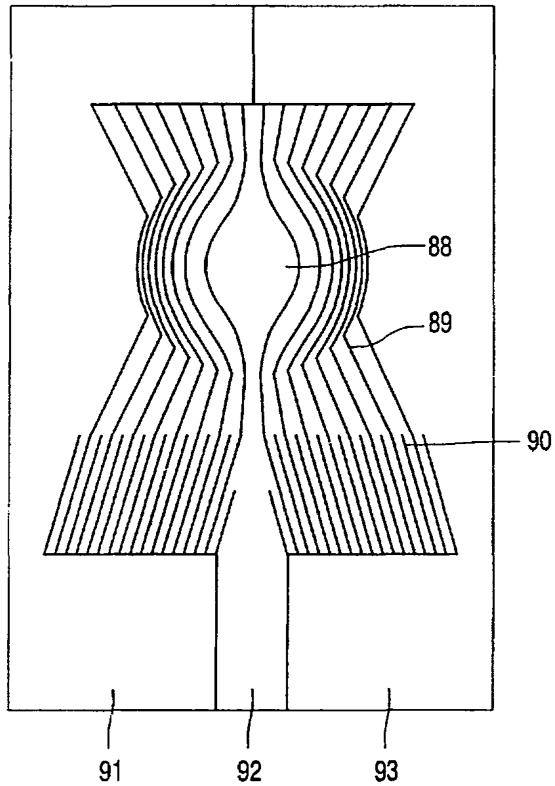


FIG. 10

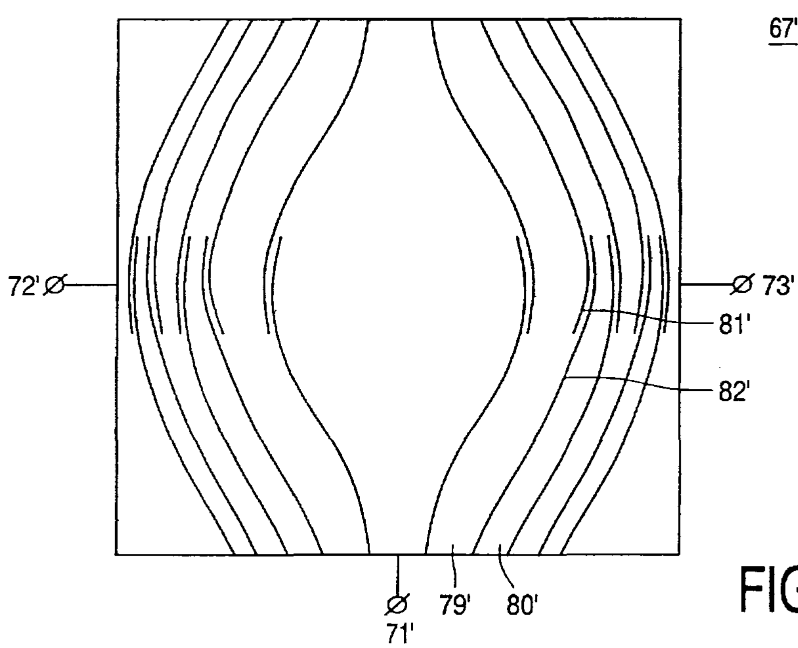
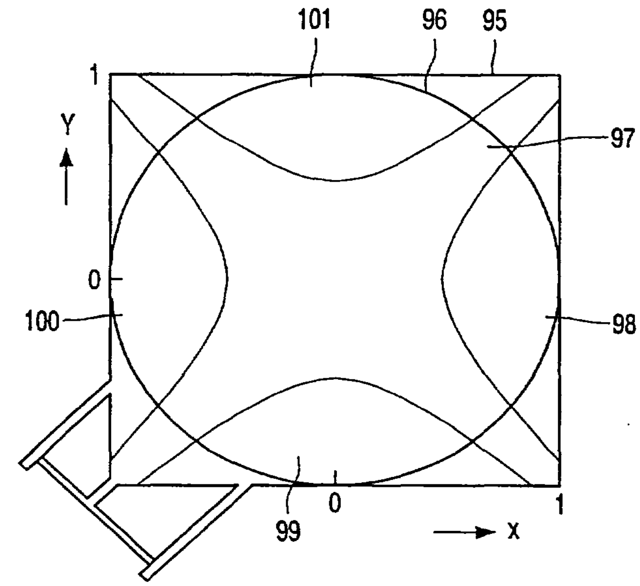


FIG. 11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99
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1
X

FIG. 12

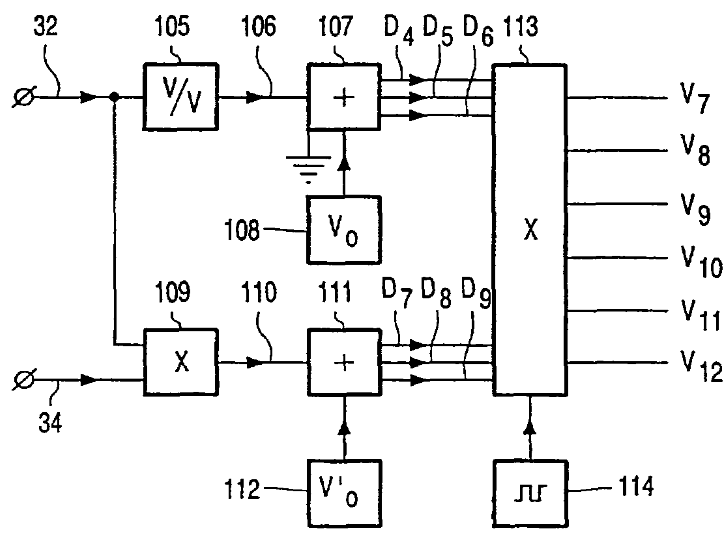
32
105
V/V
106
107
+
D4 D5 D6
113
V7
V8
V9
V10
V11
V12
X
108
V0
109
X
110
111
+
D7 D8 D9
34
112
V'0
114

FIG. 13

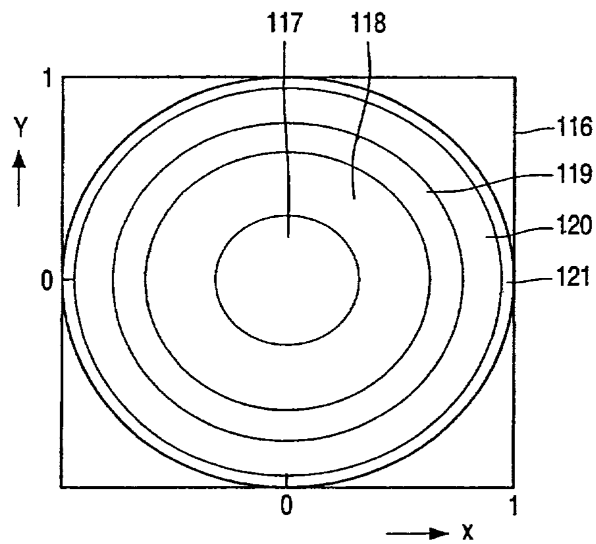

FIG. 14

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 00/12991

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G11B7/135 G02F1/1343

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G11B G02F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,X	EP 1 011 009 A (MATSUSHITA ELECTRIC IND CO LTD) 21 June 2000 (2000-06-21) column 9, line 45 -column 10, line 5; claim 1; figure 3	1,2,5
A	US 5 936 923 A (OOTAKI SAKASHI ET AL) 10 August 1999 (1999-08-10) the whole document	1
A	EP 0 911 681 A (SEIKO EPSON CORP) 28 April 1999 (1999-04-28) claims 1-3; figure 1	1
A	GB 2 276 465 A (MARCONI GEC LTD ;PURVIS ALAN (GB)) 28 September 1994 (1994-09-28) claim 1; figure 1	1

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 May 2001	30/05/2001

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

Internatio... Application No
PCT/EP 00/12991

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5 859 818 A (MURAO NORIAKI ET AL) 12 January 1999 (1999-01-12) claim 1; figures 1,3	1

2

Form PCT/ISA/210 (continuation of second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP 00/12991

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 1011009 A	21-06-2000	JP 2000235727 A	29-08-2000
US 5936923 A	10-08-1999	JP 9128785 A	16-05-1997
EP 0911681 A	28-04-1999	WO 9848321 A	29-10-1998
GB 2276465 A	28-09-1994	NONE	
US 5859818 A	12-01-1999	JP 10079135 A	24-03-1998

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9/7

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(74) Agent: **VISSER, Derk**; Internationaal Octrooibureau B.V., Prof. Holstlaan 6, NL-5656 AA Eindhoven (NL).

(81) Designated States *(national)*: CN, JP, KR, US.

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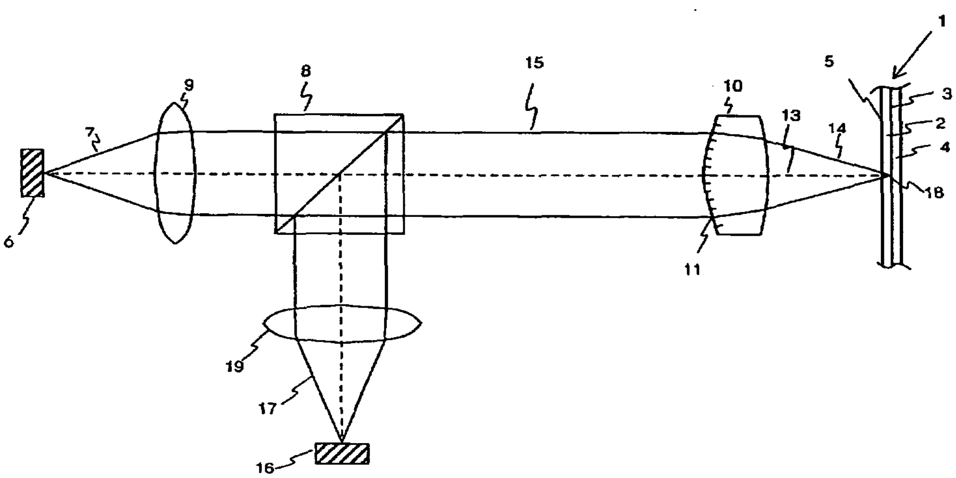
Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: OPTICAL SCANNING DEVICE



(57) Abstract: An optical scanning device for scanning of a first, second and third type of optical record carrier with radiation of a first wavelength η1, a second wavelength η2 and a third wavelength η3, respectively, where the three wavelengths are substantially different. The device comprises: a radiation source for emitting a beam of said radiation, an objective system for converging the beam on a selected one of the optical record carriers, and a phase structure arranged in the path of the beam, the phase structure comprising a plurality of phase elements of different heights, forming a non-periodic stepped profile of optical paths in the beam, and is characterised in that the stepped profile substantially approximates a flat wavefront at the first wavelength η1, a spherical aberration wavefront at the second wavelength η2, and a flat or spherical aberration wavefront at the third wavelength η3.

WO 02/082437 A1

Optical scanning device

The present invention relates to an optical scanning device comprising an optical objective lens. One particular illustrative embodiment of the invention relates to an optical scanning device that is capable of reading data from three different types of optical record carriers, such as compact discs (CDs), conventional digital versatile discs (DVDs) and so-called next generation DVDs .

These so-called next generation DVDs have recently been proposed following the advent of blue laser diodes that emit light at a significantly shorter wavelength than the red laser diodes used to read or write data from conventional DVDs. As the wavelength of the blue laser diode is shorter than that of more commonly used red laser diodes, the blue laser diode can form a smaller spot on the DVD, and hence the tracks of next generation DVDs can be more closely spaced than those of conventional DVDs, which in turn means that these next generation DVDs can have a greater data storage capacity than conventional DVDs – typically at least a twofold increase in storage capacity can be obtained.

Conventional DVDs and next generation DVDs will be referred to herein, as is usual in the art, as Red-DVDs and Blue-DVDs respectively.

To avoid customers having to purchase a variety of different devices for reading or writing data from or to specific types of optical record carrier, it is desirable for a single optical scanning device to be capable of reproducing data, for example, from a number of optical record carriers of different formats.

However, this laudable aim is not as easy to accomplish as it might otherwise seem – principally because these different format record carriers and associated scanning devices have varying characteristics.

For example, CDs are available, *inter alia*, as CD-A (CD-audio), CD-ROM (CD–read only memory) and CD-R (CD-recordable), and are designed to be scanned with a laser wavelength of about 780nm and a numerical aperture (NA) of 0.45. Red-DVDs, on the other hand, are designed to be scanned at a laser wavelength in the region of 660nm, and Blue-DVDs are designed to be scanned at a laser wavelength in the region of 405nm. For reading DVDs an NA of 0.6 is generally used, whereas for writing DVDs an NA of 0.65 is generally required.

A complicating factor is, that discs designed to be read out at a certain wavelength are not always readable at another wavelength. An example is the CD-R in which special dyes had to be applied in the recording stack in order to obtain a high modulation at 785 nm wavelength. At 660 nm wavelength the modulation of the signal from the disc becomes so small due to the wavelength sensitivity of the dye that readout at this wavelength is not feasible. On the other hand when introducing a new system with higher data capacities it is important that the new devices for reading and writing are backward compatible with the existing record carriers in order to obtain a high acceptance level in the market. Therefore, the DVD system must contain a 785 nm laser and a 660 nm laser to be able to read all existing CD types. A similar reasoning holds when reading DVD dual layer disks designed for 660 nm with a blue laser. Consequently, a system capable of reading all CD and DVD red/blue must contain a 785 nm laser, 660 nm laser and a 405 nm laser.

DVDs and CDs also differ in the thickness of their transparent substrates, which typically act as a protective layer for the data carrying layer of the disk, and as a result the depth of the data layer from the entrance face of the record carrier varies from record carrier type to record carrier type. For example, the data layer depth for DVDs is about 0.6mm, whereas the data layer depth for CDs is about 1.2mm. The spherical aberration incurred by the radiation beam traversing the protective layer is generally compensated in the objective lens of the optical scanning device.

As a result of these different characteristics for different media, problems can result if it is attempted to read data, for example, from an record carrier with an optical scanning device that has been optimised for another, different type of record carrier. For example, large amounts of spherical aberration and a non-negligible amount of spherochromatism can be caused if one type of carrier medium is read with an objective lens that has been optimised for another. The device could be provided with three objective lenses, one for each wavelength. However, this solution would be relatively expensive.

It would therefore be highly preferable to provide a device which has a single optical objective lens for scanning a variety of different optical carrier mediums using different wavelengths of laser radiation.

To this end, it has previously been proposed, in WO 99/57720 for example, to provide systems that are capable of reading data from Red-DVDs and CDs with laser radiation of different wavelengths, whilst using the same objective lens. This document describes a system which uses a moulded plastic objective lens having either two refractive aspheric surfaces or one aspherical surface and one refractive spherical surface including a diffractive

element. The lens is capable of correcting for the different spherical aberration caused by the different thickness of the two disc formats as well as for chromatic aberration caused by the different reading wavelengths.

Messrs Katayama, Komatsu and Yamanaka have designed another system which is described in their Applied Optics article entitled: "Dual-Wavelength optical head with a wavelength selective filter for 0.6 and 1.2mm thick substrate optical disks" (see Applied Optics, Volume 38, No. 17 dated 10 June 1999, page 3778.). Their system comprises a wavelength selective filter which is placed between the laser sources and the objective lens, and which varies the phase distribution of light transmitted through the filter as the wavelength of the light is changed. The filter comprises a concentric phase filter pattern and an interference filter pattern which are formed on the inner region and the outer region, respectively, of a circle whose diameter is less than the objective lens diameter. The interference filter pattern transmits 650nm light and reflects 780nm light. This means that the NA for 650nm light is equal to the maximum NA of the objective lens (i.e. about 0.6), whereas the NA for 780nm light is determined by the diameter of the circle and is about 0.45. The phase filter pattern comprises a silicon dioxide stepped structure where adjacent steps are of differing height. The particular heights of the steps are chosen so that the phase distribution of transmitted 650nm light is not affected by the filter, and so that the phase distribution of transmitted 780nm light is altered to compensate for the spherical aberration and spherochromatism that would otherwise occur. A similar method was described in a document by Messrs Hendriks, de Vries and Urbach published in the proceedings of the Optical Design and Fabrication conference held in Tokyo 2000 on page 325-328 entitled "Application of non-periodic phase structures in optical systems". In this paper also a method was presented to determine the optimum zone distribution.

Whilst each of these previously proposed systems provide a solution for situations where two different optical media are illuminated with two associated different wavelengths of light, they do not provide assistance in situations where it is desired to illuminate and scan more than two different types of carrier media with associated different wavelengths of light.

Accordingly, it is an object of the present invention to alleviate these problems by, for example, providing an optical scanning device for scanning more than two different types of optical record carriers using radiation of more than two wavelengths.

In accordance with a first aspect of the invention, there is provided an optical scanning device for scanning of a first, second and third type of optical record carrier with radiation of a first wavelength λ_1, a second wavelength λ_2 and a third wavelength λ_3, respectively, the three wavelengths being substantially different, the device comprising: a radiation source for emitting a beam of said radiation, an objective system for converging the beam on a selected one of the optical record carriers, and a phase structure arranged in the path of the beam, the phase structure comprising a plurality of phase elements of different heights, forming a non-periodic stepped profile of optical paths in the beam, characterised in that the stepped profile substantially approximates a flat wavefront at the first wavelength λ_1, a spherical aberration wavefront at the second wavelength λ_2, and a flat or spherical aberration wavefront at the third wavelength λ_3.

By virtue of this arrangement it is possible to scan optical carriers with a plurality of different radiation wavelengths, which in turn means that it is possible to provide a single device for scanning a number of different types of optical record carriers.

It is worth noting at this juncture that "flat" as used herein only implies that after taking modulo 2π of the wavefront, the resulting wavefront is constant, hence the non-periodic phase structure only introduces a constant phase offset. The term "flat" does not necessarily imply that the wavefront exhibits a zero phase change. A second aspect of the invention relates to a lens for use in an optical device for scanning a first, second and third type of optical record carrier with a beam of radiation of a first wavelength λ_1, a second wavelength λ_2 and a third wavelength λ_3, respectively, the three wavelengths being substantially different, the lens comprising:

a phase structure arranged in the path of the beam, the phase structure comprising a plurality of phase elements of different heights, forming a non-periodic stepped profile of optical paths in the beam,

characterised in that the stepped profile substantially approximates a flat wavefront at the first wavelength λ_1, a spherical aberration wavefront at the second wavelength λ_2, and a flat or spherical aberration wavefront at the third wavelength λ_3.

Various preferred embodiments of each of these aspects are set out in respective accompanying dependent claims.

Another aspect of the invention relates to an optical scanning device for scanning Red-DVDs, CDs and Blue-DVDs with radiation of a first wavelength λ_1, a second wavelength λ_2 and a third wavelength λ_3 respectively, the device comprising: a phase

structure formed on a face of an objective lens, said phase structure being comprised of a plurality of phase elements for introducing phase changes in a beam of said radiation, said phase elements being arranged in a stepped profile with step heights across a diameter of the lens being substantially as follows: 14.040 μm, 5.850 μm, -2.340 μm, 5.850 μm and 14.040 μm; wherein λ_1 is substantially 660nm, λ_2 is substantially 785nm and λ_3 is substantially 405nm.

Yet another aspect of the invention relates to an objective lens for use in an optical scanning device for scanning Red-DVDs, CDs and Blue-DVDs with radiation of a first wavelength λ_1, a second wavelength λ_2 and a third wavelength λ_3 respectively, the lens comprising: a phase structure formed on a face of the lens, said phase structure being comprised of a plurality of phase elements for introducing phase changes in a beam of said radiation, said phase elements being arranged in a stepped profile with step heights across a diameter of the lens being substantially as follows: 14.040 μm, 5.850 μm, -2.340 μm, 5.850 μm and 14.040 μm; wherein λ_1 is substantially 660nm, λ_2 is substantially 785nm and λ_3 is substantially 405nm.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Fig. 1 is a schematic illustration of components of a scanning device for optical record carriers according to one embodiment of the present invention;

Fig. 2 is a schematic illustration of an objective lens for use in the scanning device of Figure 1;

Fig. 3 is a schematic front view of the objective lens of Fig. 2; and

Fig. 4 is a cross-sectional view along the line A- - -A of Fig. 3. The first step on the left starts in the middle of Fig 3.

The illustrative embodiments of the invention that will now be described refer to a phase structure for use in a system for scanning CDs, Red-DVDs and Blue-DVDs. However, it should be noted that this description is purely illustrative and that the teachings of the invention may be applied in the construction of devices which can scan more than three

media. As a result, the forthcoming description should not be construed as limiting the scope of the invention in any way.

Figure 1 is a schematic illustration of components common to a device in accordance with the embodiment, to be described below, for scanning an optical record carrier 1. The record carrier 1 is in this embodiment an optical disc as will be described, by way of example, below.

The optical disc 1 comprises a transparent layer 2, on one side of which at least one information layer 3 is arranged. The side of the information layer facing away from the transparent layer is protected from environmental influences by a protection layer 4. The side of the transparent layer facing the device is the disc entrance face 5. The transparent layer 2 acts as a substrate for the optical disc by providing mechanical support for the information layer or layers. Alternatively, the transparent layer 2 may have the sole function of protecting the information layer 3, while the mechanical support is provided by a layer on the other side of the information layer, for instance by the protection layer 4 or by a further information layer and transparent layer connected to the uppermost information layer.

Information may be stored in the information layer 3, or information layers, of the optical disc in the form of optically detectable marks arranged in substantially parallel, concentric or spiral tracks, not indicated in Figure 1. The marks may be in any optically readable form, e.g. in the form of pits, or areas with a reflection coefficient or a direct of magnetisation different from their surroundings, or a combination of these forms.

The scanning device includes a radiation source 6, comprising a tuneable semiconductor laser or three separate semiconductor lasers, emitting radiation of first, second and third wavelengths in a diverging radiation beam 7 towards a lens system. The lens system includes a collimator lens 9 and an objective lens 10 arranged along optical axis 13. The collimator lens 9 transforms the diverging beam 7 emitted from the radiation source 6 into a substantially collimated beam 15. The objective lens 10 comprises a phase element (or phase structure), which is indicated in the drawing by the pattern 11 and which will be described in more detail below. The objective lens 10 transforms the incident collimated radiation beam 15 into a converging beam 14, having a selected NA, which comes to a spot 18 on the information layer 3. A detection system 16, a second collimator lens 19 and a beam splitter 8 are provided in order to detect data signals, and focus error signals which are used to mechanically adjust the axial position of the objective lens 10.

The phase grating 11 as shown in Figure 1 may be arranged on the side of the objective lens 10 facing the radiation source (referred to herein as the entry face of the lens), or alternatively on the other surface of the lens 10 (referred to herein as the exit face of the lens).

Figure 2 is a schematic illustration of the objective lens 10 for use in the scanning device described above. The scanning device is capable of scanning optical record carriers with a first information layer depth with laser radiation 21 of a first wavelength at a first numerical aperture. The device is further capable of scanning record carriers with a second information layer depth with laser radiation 23 of second and third wavelengths at a second numerical aperture using the same optical objective lens 10. Discs of Red-DVD format may be scanned with laser radiation of a first wavelength λ_1 between say 620 and 700nm, preferably λ_1=660nm. A numerical aperture of about 0.6 is used for reading Red-DVDs and an NA above 0.6, preferably 0.65, is applied for writing to Red-DVDs. Record carriers of CD format are scanned with laser radiation of a second wavelength λ_2 between say 740 and 820nm, preferably λ_2=785nm with a numerical aperture of below 0.5, preferably 0.45. Discs of Blue-DVD format may be scanned with laser radiation of a third wavelength λ_3 between say 365 and 445nm, preferably λ_3=405nm.

The phase structure 11 on the objective lens 10 is arranged to compensate for spherical aberration caused by the difference in thickness 31 and 33 of the transparent layers of a Red-DVD or Blue-DVD and a CD carrier, respectively. The structure similarly corrects for spherochromatism and chromatic aberration. Effectively, the phase structure 11 is designed to introduce an amount of wavefront deviation in light passing therethrough which compensates for the spherical aberration caused by, for example, a change in information layer depth.

In this embodiment of the invention, reading and writing data on discs of a different format using a single objective element is achieved by using a hybrid lens in an infinite-conjugate mode. Such a hybrid lens can be formed by applying a phase profile on one of the surfaces of a refractive lens, for example by a lithographic process or by diamond turning.

The objective lens 10 is shown as a convex-convex lens; however other lens element types such as plano-convex or convex-concave lenses may also be used. Whilst the objective system is in this embodiment a single lens, it may be a compound lens containing two or more lens elements. The objective lens 10 may for example include a refractive objective lens element and a planar lens phase element. The phase element or phase structure may also

comprise or be provided on an optical element in the objective system or separate from the objective system, for example on a quarter wavelength plate or a beam splitter.

Figure 3 is a schematic front view of the objective lens 10 illustrating the phase structure. It can be seen that a circular structure has been applied with a pattern of coaxial annular ring-shaped pattern elements with gradually increasing width towards the centre of the lens. Each pattern element defines a so-called zone of the phase element. In order to enable operation of the lens for multiple wavelengths in an infinite-conjugate manner, the lens generates a different amount of spherical aberration (i.e. a different amount of wavefront deviation) for each wavelength to correct for aberrations resulting, for example, from differences in disc thicknesses.

The generation of different spherical aberrations is achieved by arranging the phase structure so that the zones of the structure are of differing heights, the heights being chosen so that a phase difference is introduced into the beam passing through the lens – the particular phase difference applied to a given wavelength being chosen to counteract the various detrimental effects of the types described above.

In this connection, it is important to note that the phase structure employed in embodiments of the invention has a non-periodic pattern, and therefore does not form diffraction orders. As a consequence of this, the phase structure to be described does not exhibit inherent losses of the type that might be exhibited by a diffraction grating.

The first step in designing a suitable phase structure is to choose one wavelength as a "design wavelength" and to optimise the optical system for that wavelength. This means that any phase structure applied to the lens 10 should not affect a beam of the design wavelength passing therethrough. Hence it should result in a substantially flat wavefront. In other words, the phase structure should only introduce a phase change that is equal to a constant plus a multiple of, approximately 2π radians. It should be noted that the term "multiple" as used herein should be construed to include any integer, including negative integers, 0 and 1.

As is well known, the phase change φ introduced into a beam of wavelength λ_1 as that beam passes through a step of height h, may be written as:

$$\phi_{\lambda_1} = 2\pi\left(n_{\lambda_1} - n_0\right)\frac{h}{\lambda_1} \qquad (1)$$

where $n_{\lambda 1}$ is the refractive index of the step for light of wavelength λ_1, and n_0 is the refractive index of the preceding medium before entering the step (n_0=1 if the preceding medium is air).

As mentioned above, for the design wavelength φ should be equal to 2π or to an integer multiple thereof (so that the phase structure has no effect on light of the design wavelength).

Putting φ equal to 2π enables Equation (1) to be rearranged for h to give the height h_1 of a step which at wavelength λ_1 gives rise to a phase change of 2π:

$$h_1 = \frac{\lambda_1}{\left(n_{\lambda_1} - n_0\right)} \qquad (2)$$

Similar expressions may be derived for h_2 (the height of step required to give a 2π phase change at λ_2) and h_3 (the height of step required to give a 2π phase change at λ_3).

$$h_2 = \frac{\lambda_2}{\left(n_{\lambda_2} - n_0\right)} \qquad (3)$$

$$h_3 = \frac{\lambda_3}{\left(n_{\lambda_3} - n_0\right)} \qquad (4)$$

Let us now consider what phase change a step of height h_1 will have on light of wavelength λ_2 and λ_3 passing therethrough. From Equation (1) we can write:

$$\varphi_{\lambda_2} = 2\pi\left(n_{\lambda_2} - n_0\right)\frac{h_1}{\lambda_2} \qquad \text{or} \qquad (5)$$

$$\frac{\lambda_2 \varphi_{\lambda_2}}{2\pi\left(n_{\lambda_2} - n_0\right)} = h_1$$

Substituting for h_1 from Equation (2) gives:

$$\frac{\lambda_2 \varphi_{\lambda_2}}{2\pi\left(n_{\lambda_2} - n_0\right)} = \frac{\lambda_1}{\left(n_{\lambda_1} - n_0\right)} \qquad \text{or} \qquad (6)$$

$$\varphi_{\lambda_2} = 2\pi \frac{\left(n_{\lambda_2} - n_0\right)}{\left(n_{\lambda_1} - n_0\right)} \frac{\lambda_1}{\lambda_2} \qquad (7)$$

If we then substitute in Equation (7) for λ_1 and λ_2 (from Equations (2) & (3)), we have:

$$\varphi_{\lambda_2} = 2\pi \frac{\left(n_{\lambda_2} - n_0\right)}{\left(n_{\lambda_1} - n_0\right)} \frac{\left(n_{\lambda_1} - n_0\right) h_1}{\left(n_{\lambda_2} - n_0\right) h_2} \qquad \text{or} \qquad (8)$$

$$\varphi_{\lambda_2} = 2\pi \frac{h_1}{h_2} \qquad (9)$$

A similar expression can be derived for $\varphi_{\lambda 3}$:

$$\varphi_{\lambda_3} = 2\pi \frac{h_1}{h_3} \qquad (10)$$

It can therefore be seen that a step of height h_1, which introduces a phase change of 2π for radiation of wavelength λ_1 introduces a phase change of $2\pi(h_1/h_2)$ and $2\pi(h_1/h_3)$ for radiation of the second and third wavelengths, respectively.

At multiples, m, of the step height h_1, it will be apparent from equations (9) and (10) that the phase difference at the second and third wavelengths will vary as: $2\pi m(h_1/h_2)$ and $2\pi m(h_1/h_3)$, respectively.

However, because (h_1/h_2) and (h_1/h_3) can be approximated by rational numbers, multiples of the step height h_1 will only give rise to a *limited* number of substantially different phase steps at the other two wavelengths – the number of different phase steps being equal to the number of times the rational number (h_1/h_2) or (h_1/h_3) can be summed until the resultant phase change φ is at least approximately an integer multiple of 2π.

Let p_2 be the number of different steps for λ_2, and p_3 be the number of different steps for λ_3.

As p_2 and p_3 are different, different combinations of phase steps for λ_2 and λ_3 can be selected simply by selecting different integer multiples, m, of step height h_1. In other words, the teachings of this invention enable a phase structure to be formed which introduces a phase difference of 2π at the design wavelength, and any combination of the aforementioned discrete phase differences at other wavelengths.

If we now consider the specific example of a device for reading data from Red-DVDs, Blue-DVDs and CDs we can calculate the appropriate step heights for the phase structure which will enable data read-out to be achieved from each of the three different media using three discrete wavelengths of light and a single objective lens.

As mentioned above, Red-DVDs are read with light of wavelength 660nm. Accordingly, in this example our design wavelength λ_1= 660nm, and at this wavelength we require the phase structure to introduce an integer multiple of 2π phase difference in light

passing therethrough. The second wavelength, λ_2, is equal to 785nm for reading data from CDs, and the third wavelength, λ_3, is equal to 405nm for reading data from Blue-DVDs.
In the case where the phase structure 11 is of diacryl, $n_{\lambda 1}=1.564$, $n_{\lambda 2}=1.559$ and $n_{\lambda 3}=1.594$. If we assume that $n_0=1$, it is possible to calculate using Equations (2), (3) and (4) the step heights h_1, h_2 and h_3 to be 1.170µm, 1.404µm and 0.682µm respectively.

From Equations (9) and (10) it can be calculated that the phase difference introduced by a step of height h_1 in a beam of wavelength λ_2 and λ_3 is equal to $2\pi(0.833)$ radians for λ_2, and $2\pi(1.716)$ radians for λ_3. Since $0.8333 \sim 5/6$ and $1.716 \sim 12/7$ we have $p_2=6$ and $p_3=7$.
If we tabulate this data for multiples, m, of the step height h_1 we can construct a table, thus:

Table 1

Phase Difference at λ_2 and λ_3 introduced by a step of height mh_1

m	Phase $\varphi_{\lambda 2}$ (mod 2π) radians	Phase $\varphi_{\lambda 3}$ (mod 2π) radians
-2	2.094	3.575
-1	1.047	1.787
0	0.000	0.000
1	***5.235***	4.496
2	***4.188***	2.709
3	***3.142***	0.921
4	***2.094***	***5.417***
5	***1.047***	***3.630***
6	***0.000***	***1.843***
7	5.235	***0.055***
8	4.188	***4.551***
9	3.142	***2.764***
10	2.094	***0.977***
11	1.047	5.472
12	0.000	3.685

From Table 1, it can be seen that p_2 is equal to six and that p_3 is equal to seven (see the emboldened and italicised numbers in columns φ_2 and φ_3 respectively), and further that each set of discrete phase steps repeats *ad infinitum* with increasing ranges of multiples m of the step height h_1. For example, φ_2 runs from m=1 to m=6, and then repeats from m=7 to m=12. Similarly, φ_3 runs from m=4 to m=10, and then repeats from m=11 to m=17 (not shown).

As p_2 and p_3 are different, every combination of discrete phase steps for λ_2 and λ_3 is available for selection simply by selecting the appropriate multiple m of the step height h_1.

In general terms, it is possible to determine a mathematical expression for the number p_i of substantially different phase steps for a step height h_i at a wavelength λ_i as will now be shown.

If we define h_1 to be the height of a phase structure which introduces a phase step of 2π at wavelength λ_1, and similarly h_i to be the height of a structure which introduces a phase step

of 2π at another wavelength λ_i. Then, to find the number p_i of substantially different phase steps for the height h_i corresponding to λ_i we write the ratio h_1/h_i as a Continued Fraction CF^i. In general a continued fraction (CF) is defined by:

$$CF = b_0 + \cfrac{1}{b_1 + \cfrac{1}{b_2 + \cfrac{1}{b_3 + \cfrac{1}{b_4 + \ldots\ldots}}}} \equiv b_0 + \frac{1}{b_1 +}\,\frac{1}{b_2 +}\,\frac{1}{b_3 +}\ldots\ldots \qquad (11)$$

This last equation is just another notation for a CF (see for instance Page 19 of the "Handbook of mathematical functions", by M. Abramowitz and I.A. Stegun (Dover Publications, New York,1970)).

When the numbers b_k are integer numbers the CF always converges. As a result, we can define the truncation of this CF to the m^{th} order to be CF_m which can be written as:

$$CF_m = b_0 + \frac{1}{b_1 +}\,\frac{1}{b_2 +}\,\frac{1}{b_3 +}\ldots\ldots\frac{1}{b_m} = \frac{A_m}{B_m} \equiv \{b_0, b_1, b_2, \ldots\ldots, b_m\} \qquad (12)$$

where A_m and B_m are integers determined by

$$\begin{aligned} A_m &= b_m A_{m-1} + A_{m-2} \\ B_m &= b_m B_{m-1} + B_{m-2} \\ A_{-1} &= 1,\ A_0 = b_0,\ B_{-1} = 0,\ B_0 = 1 \end{aligned}$$

For instance, we have

$$CF_4 = b_0 + \cfrac{1}{b_1 + \cfrac{1}{b_2 + \cfrac{1}{b_3 + \cfrac{1}{b_4}}}} \equiv b_0 + \frac{1}{b_1 +}\,\frac{1}{b_2 +}\,\frac{1}{b_3 +}\,\frac{1}{b_4} \qquad (13)$$

The coefficients b_k can be determined as follows. Let

$$a_0 = \frac{h_1}{h_i} \qquad 14$$

Then we find

$$b_0 = \mathrm{Int}[a_0] \qquad (15)$$

where Int[] means taking the integer part of a_0 (for instance Int[3.253]=3).

If we then define

$$a_1 = a_0 - b_0$$

and let

$$b_1 = \mathrm{Int}[\frac{1}{a_1}] \qquad (17)$$

$$a_2 = \frac{1}{a_1} - b_1 \qquad (18)$$

We have

$$b_m = \mathrm{Int}[\frac{1}{a_m}] \qquad (19)$$

$$a_{m+1} = \frac{1}{a_m} - b_m \qquad (20)$$

and the CF_m is uniquely defined. To find the number p_i we must determine the CF_k^i corresponding to h_1/h_i such that for that integer value of k the CF_k^i satisfies the relation

$$\left| CF_k^i - \frac{h_1}{h_i} \right| \leq 0.005 \qquad (21)$$

for the first time. The rational approximation is then

$$\frac{h_1}{h_i} \approx CF_k = \frac{A_k}{B_k} \qquad (22)$$

and from this we find that the number p_i of substantially different phase steps for the height h_i corresponding to λ_i is given by

$$p_i = B_k \qquad (23)$$

This can be seen as follows.

$$\begin{aligned} \varphi_{\lambda_i} &= 2\pi(m + p_i)\frac{h_1}{h_i} \\ &\approx 2\pi m\frac{h_1}{h_i} + 2\pi p_i\frac{A_k}{B_k} \qquad (25) \\ &\approx 2\pi m\frac{h_1}{h_i} + 2\pi A_k \end{aligned}$$

If we take a step height of mh_1 with m integer, the phase change introduced at wavelength λ_i is then given by

$$\varphi_{\lambda_i} = 2\pi m\frac{h_1}{h_i} \qquad (24)$$

If we consider now the height $(m+ p_i)\, h_1$, the same phase for λ_i as with the height mh_1 is expected. This can be shown as follows:

Since A_k is an integer number, the phase modulo 2π introduced by the step heights mh_1 and $(m+ p_i)\, h_1$ are substantially equal.

If we now consider the case where the phase structure 10 is made of diacryl, $n_{\lambda 1}=1.564$, $n_{\lambda 2}=1.559$ and $n_{\lambda 3}=1.594$. If we assume that $n_0=1$, it is possible to calculate using Equations (2), (3) and (4) the step heights h_1, h_2 and h_3 to be 1.170 μm, 1.404 μm and 0.682 μm respectively.

From Equations (9) and (10) it can also be calculated that the phase difference introduced by a step of height h_1 in a beam of wavelength λ_2 and λ_3 is equal to $2\pi(0.833)$ radians for λ_2, and $2\pi(1.716)$ radians for λ_3. Expanding the ratio's $h_1/h_2=0.833$ and $h_1/h_3=1.716$ in a continued fraction as explained above (see table III and IV) we find that $0.8333{\sim}5/6$ and $1.716{\sim}12/7$, hence we have $p_2=6$ and $p_3=7$.

Table II: $h_1/h_2=0.833$

k	CF_k^2	A_k/B_k	$\lvert CF_k^2 - 0.833\rvert$	B_k
1	{0,1}	1/1	0.167	1
2	{0,1,4}	4/5	0.033	5
3	{0,1,4,1}	5/6	0.000	6

Table III: $h_1/h_3=1.716$

k	CF_k^3	A_k/B_k	$\lvert CF_k^3 – 1.716\rvert$	B_k
1	{1,1}	2/1	0.284	1
2	{1,1,2}	5/3	0.049	3
3	{1,1,2,1}	7/4	0.034	4
4	{1,1,2,1,1}	12/7	0.002	7

In conclusion, it is possible to express the number p_i of substantially different phase steps for the height h_i corresponding to λ_i as follows. Write the ratio h_1/h_i as a Continued Fraction CF^i according to Equation (11); truncate the fraction as soon as the condition set out in Equation (21) is met; determine the values A_k and B_k; and the number of substantially different phase steps for the height h_i corresponding to λ_i is then given by $p_i = B_k$.

The objective lens 10 in Figure 2, in this example, is a plano-aspherical element. The objective lens 10 has thickness on the optical axis of 2.401 mm and entrance pupil diameter of 3.3 mm. The lens body of the objective lens is made of LAFN28 Schott glass with refractive index n=1.7682 at wavelength λ_1=660 nm, n=1.7625 at λ_2=785 nm and n=1.7998 at λ_3=405 nm. The convex surface of the lens body which is directed towards the collimator lens has radius 2.28 mm. The surface of the objective lens facing the record carrier is flat. The aspherical shape is realized in a thin layer of acryl on top of the glass body. The lacquer has refractive index n=1.5640 at 660 nm, n=1.5588 at 785 nm and n=1.5945 at 405 nm. The thickness of this layer on the optical axis is 17 microns. The rotational symmetric aspherical shape is given by the equation

$$z(r) = \sum_{i=1}^{5} B_{2i} r^{2i}$$

with z the position of the surface in the direction of the optical axis in millimeters, and r the distance to the optical axis in millimeters, and B_k the coefficient of the k-th power of r. The value of the coefficients B_2 until B_{10} are 0.239104, 0.0050896354, 8.9127376 10^{-5}, -8.7208131 10^{-5}, -1.8258426 10^{-6}, respectively. The free working distance hence the distance between the objective lens 10 and the disk is 1.049 mm for DVD at λ_1=660 nm with cover layer thickness of the disk is 0.6 mm, 0.6952 mm for CD at λ_2=785 nm with cover layer thickness of the disk is 1.2 mm and 0.9710 mm for DVD at λ_3=405 nm with cover layer thickness of the disk is 0.6 mm. The cover layer thickness of the disk is made of polycarbonate with refractive index n=1.5798 at wavelength λ_1=660 nm, n=1.5731 at wavelength λ_2=785 nm and n=1.6188 at wavelength λ_3=405 nm. The objective is designed in such a way that when reading a DVD at 660 nm and DVD disk at 405 nm no spherochromatism is introduced. Hence the objective is already suited for DVD red and blue readout. In order to make the lens suitable for CD readout the spherical aberration arising due to the disk thickness difference and the spherochromatism has to be compensated. Using the method described by Messrs Katayama, Komatsu and Yamanaka described in their Applied Optics article entitled: "Dual-Wavelength optical head with a wavelength selective filter for 0.6 and 1.2mm thick substrate optical disks" (see Applied Optics, Volume 38, No. 17 dated 10 June 1999, page 3778) and similar by Messrs Hendriks, de Vries and Urbach described in the proceedings of the Optical Design and Fabrication conference held in Tokyo 2000 on page 325-328 entitled "Application of non-periodic phase structures in optical systems", it is possible to compensate for spherical aberrations and spherochromatism in a Red-DVD / CD

system by providing a three phase step structure which introduces a relative phase in the CD case (i.e. when the optical medium is scanned with light at a wavelength of approximately 785nm) of 0.00 radians, 1.047 radians and 2.094 radians; and a relative phase in the Red-DVD case of approximately 2π radians and integer multiples thereof (see tables 1 and 4).

From table 1 it is apparent that appropriate phase differences for correcting aberrations and other defects at the CD wavelength λ_2 may be provided by constructing a phase structure with steps of $0h_1$, $5h_1$ and $4h_1$ or $0h_1$, $-1h_1$ and $-2h_1$, for example.

However, if it is also desired to scan Blue-DVDs as well as CDs then the step heights chosen for scanning at the CD wavelength λ_2 must not introduce any appreciable phase gradient when the objective is illuminated with light of the Blue-DVD wavelength λ_3.

If we again refer to Table 1, it is apparent that by picking step heights of $12h_1$, $5h_1$ and $-2h_1$ (for example) we will introduce the desired phase difference of 0.00, 1.047 and 2.094 radians at the CD wavelength λ_2 and, in addition, an approximately equal phase difference of roughly 3.6 radians at the Blue-DVD wavelength λ_3.

As there is no appreciable phase gradient at the Blue-DVD wavelength, the roughly constant phase change caused by the phase structure has no effect upon scanning of Blue-DVDs.

In other words, by constructing a phase structure with step heights of $12h_1$, $5h_1$ and $-2h_1$ it is possible to provide an objective lens that enables scanning of CDs, Red-DVDs and Blue-DVDs.

At this juncture it is worth mentioning how one might go about constructing a step with a negative height. If one wished to construct a step of $-2h_1$, for example, one could add a layer of material of depth $2h_1$ to the entire surface of the lens (which gives rise to a constant wavefront offset having no influence on spot formation) and then remove the layer in those areas where it is desired to form the step.

Table 4 illustrates the measurements for a phase structure such as that described above with which it is possible to scan CDs, Red-DVDs and Blue-DVDs. Figure 4 provides an exaggerated schematic cross-sectional view along the line A—A of Figure 3, and shows a phase structure with a step height distribution such as that set out in Table 4.

Table 4: Step Height Distribution

(where: r is the radial pupil co-ordinate, and

h_j is the height, in microns, of the phase structure in zone j)

j	r_{begin} zone j	r_{end} zone j	m_j	h_j [μm]	phase CD (mod 2π)	phase Blue-DVD (mod 2π)
1	0.00	0.40	12	14.040	0.000	3.685 ≅ 3.6
2	0.40	0.59	5	5.850	1.047	3.630 ≅ 3.6
3	0.59	1.10	-2	-2.340	2.094	3.575 ≅ 3.6
4	1.10	1.20	5	5.850	1.047	3.630 ≅ 3.6
5	1.20	1.65	12	14.040	0.000	3.685 ≅ 3.6

Using such a structure it has been found that the rms wavefront aberration (which is the average optical path difference of the wavefront over the entire entrance pupil of the lens – or in other words, a measure of the aberration introduced by the lens) introduced at λ_3 is in the region of 17mλ, and at λ_2 is in the region of 43mλ.

When the rms wavefront aberration (measured in waves λ) is below 0.07λ the optical system is described as being "diffraction limited", which means that the aberrations introduced by imperfections in the lens are smaller than the width of the spot due to diffraction effects. For correct scanning, the total rms wavefront aberration of the whole optical system should be less than 0.07λ. Since the rms wavefront aberrations at λ_2 and λ_3 are less than 0.07λ (and since no appreciable aberration is introduced at the design wavelength λ_1), the system described above is suitable for scanning CDs, Red-DVDs and Blue-DVDs.

Although here only the case where at the third wavelength a flat wavefront is produced by the phase structure is considered, extending this to the case where at the third wavelength spherical aberration is produced can be done as follows. For the third wavelength there are p_3 substantially different phase steps (see for instance table 1, column 3). To compensate with these phase steps an amount of spherical aberration (which could be introduced when at the third wavelength the cover layer thickness of the disc is different form that of the first wavelength or when there is an amount of spherochromatism present) in the third configuration proceed in the same way as explained before to achieve spherical aberration correction for the CD configuration while introducing a flat wavefront for the Red-DVD and Blue-DVD case. Now the structure is designed to generate spherical aberration for

the Blue-DVD case, while it introduces a flat wavefront for the Red-DVD and the CD case. In this way we end up with two phase structure designs, one introducing the desired amount of spherical aberration for the second wavelength while having no effect for wavelength one and three; the other one introducing the desired amount of spherical aberration for the third wavelength while having no effect for wavelength one and two. The final step in the design is simply adding both structures on top of each other. The resulting phase structure will in general be more complex because the width of the plurality of phase elements of each of the two separate structures may be different.

Whilst this embodiment relates generally to the case where one wishes to read data from three different types of optical media with three associated wavelengths of light, it will be appreciated by persons skilled in the art that the teachings of this invention may be applied to systems where it is desired to read (or write) data at a greater number of wavelengths.

For example, if it were desired to additionally scan media using light of a fourth wavelength λ_4 (for example for an additional type of optical media), then table 1 would be expanded to include a fourth column of phase change φ_4 which would comprise multiples of the ratio h_1/h_4. Since λ_4 would be different to λ_1, λ_2 or λ_3, the number of discrete phase steps p_4 would also be different to p_2 or p_3. As a result, it would then be possible to select every combination of phase change φ_2, φ_3 and φ_4 simply by selecting appropriate values of m. In this way it would then be possible to provide a phase structure which enabled data read-out, for example, from four different optical media at four different wavelengths.

It can be seen therefore that the teachings of this invention may be applied to provide a device for scanning a plurality of different types of optical media, for example with associated different wavelengths of light.

From the above it will be understood that the scope of this invention extends to phase structures which approximate:

(a) a spherical aberration wavefront at the first wavelength λ_1, a flat wavefront at the second wavelength λ_2, and a flat wavefront at the third wavelength λ_3; or

(b) a spherical aberration wavefront at the first wavelength λ_1, a flat wavefront at the second wavelength λ_2, and a spherical aberration wavefront at the third wavelength λ_3.

This results from the fact that there are two effects giving rise to spherical aberration; (i) a change in refractive index resulting from a change in wavelength (called spherochromatism), and (ii) a change in cover layer thickness (for example, DVDs have a cover layer that is approximately 0.6mm thick whereas CDs have a cover layer of that is approximately 1.2mm thick).

Effect (i) is typically small in comparison with effect (ii) and as a consequence when the wavelength varies and the cover layer thickness does not vary, it is possible to compensate for spherochromatism in the lens design of the objective system (as is described herein with respect to a DVDBlue, DVDRed and CD system).

In circumstances when the cover layer thicknesses are all different or the spherochromatism cannot be compensated for, the phase structure (b) can still provide a system which is capable of reading optical data carriers with three different wavelengths.

Whilst particular preferred embodiments of the invention have been described herein, it will be understood that modifications may be made within the scope of the invention as defined in the appended claims.

For example, whilst in the embodiment described above the phase structure 11 is provided on the lens 10 it will be appreciated that the phase structure could instead be provided on an optical element separate from the objective lens, for example on a quarter wavelength plate or a beam splitter.

In addition, it will also be understood that, where the term "approximate" or "approximation" is used herein, that it is intended to cover a range of possible approximations, the definition including approximations which are in any case sufficient to provide a working embodiment of an optical scanning device serving the purpose of scanning different types of optical record carriers.

CLAIMS:

1. An optical scanning device for scanning of a first, second and third type of optical record carrier with radiation of a first wavelength λ_1, a second wavelength λ_2 and a third wavelength λ_3, respectively, the three wavelengths being substantially different, the device comprising:

a radiation source for emitting a beam of said radiation,

an objective system for converging the beam on a selected one of the optical record carriers, and

a phase structure arranged in the path of the beam, the phase structure comprising a plurality of phase elements of different heights, forming a non-periodic stepped profile of optical paths in the beam,

characterised in that the stepped profile substantially approximates a flat wavefront at the first wavelength λ_1, a spherical aberration wavefront at the second wavelength λ_2, and a flat or spherical aberration wavefront at the third wavelength λ_3.

2. The scanning device according to Claim 1, wherein $|\lambda_1-\lambda_2|$, $|\lambda_2-\lambda_3|$ and $|\lambda_1-\lambda_3|$ are each larger than 20 nm.

3. The scanning device according to Claim 2, wherein $|\lambda_1-\lambda_2|$, $|\lambda_2-\lambda_3|$ and $|\lambda_1-\lambda_3|$ are each larger than 50 nm.

4. The scanning device according to Claim 1, wherein the differences in length between the optical paths at the first wavelength λ_1 correspond to phase changes in the beam substantially equal to multiples of 2π.

5. The scanning device according to Claim 3, wherein an attainable number of substantially different phases for different heights of a phase element at the wavelength λ_2 is different from an attainable number of substantially different phase steps for different heights of a phase element at the wavelength λ_3.

6. The scanning device according to Claim 4, wherein the attainable number B_k of substantially different phase steps at wavelength λ_i for i equal to 2 and 3 is determined by an inequality

$$\left|\frac{A_k}{B_k} - \frac{h_1}{h_i}\right| \leq 0.005$$

where the integer k is the smallest positive integer that complies with the inequality and with $\frac{A_k}{B_k} = \{b_0, b_1, \ldots, b_k\}$ where $\{b_0, b_1, \ldots, b_k\}$ is a continued fraction truncated at the k^{th} term, and h_1, h_i are the heights of a phase element that introduces a 2π phase change in the optical path at the wavelengths λ_1 and λ_i respectively.

7. The scanning device according to Claim 1, wherein said phase structure exhibits a difference between a lowest phase step Φ_{min} and a highest phase step Φ_{max} at λ_1 which complies with:

$$|\Phi_{max} - \Phi_{min}| > 2\pi B_k$$

where B_k is the lowest attainable number of substantially different phase steps at one of the wavelength λ_i for i equal to 2 and 3.

8. The scanning device according to claim 1, wherein the phase structure is generally circular and the steps of said stepped profile are generally annular.

9. The scanning device according to claim 1, wherein said phase structure is formed on a face of a lens of the objective system.

10. The scanning device according to claim 1, wherein said phase structure is formed on an optical plate provided between the radiation source and the objective system.

11. The scanning device according to Claim 10, wherein said optical plate comprises a quarter wavelength plate or a beam splitter.

12. A lens for use in an optical device for scanning a first, second and third type of optical record carrier with a beam of radiation of a first wavelength λ_1, a second wavelength λ_2 and a

third wavelength λ_3, respectively, the three wavelengths being substantially different, the lens comprising:

a phase structure arranged in the path of the beam, the phase structure comprising a plurality of phase elements of different heights, forming a non-periodic stepped profile of optical paths in the beam,

characterised in that the stepped profile substantially approximates a flat wavefront at the first wavelength λ_1, a spherical aberration wavefront at the second wavelength λ_2, and a flat or spherical aberration wavefront at the third wavelength λ_3.

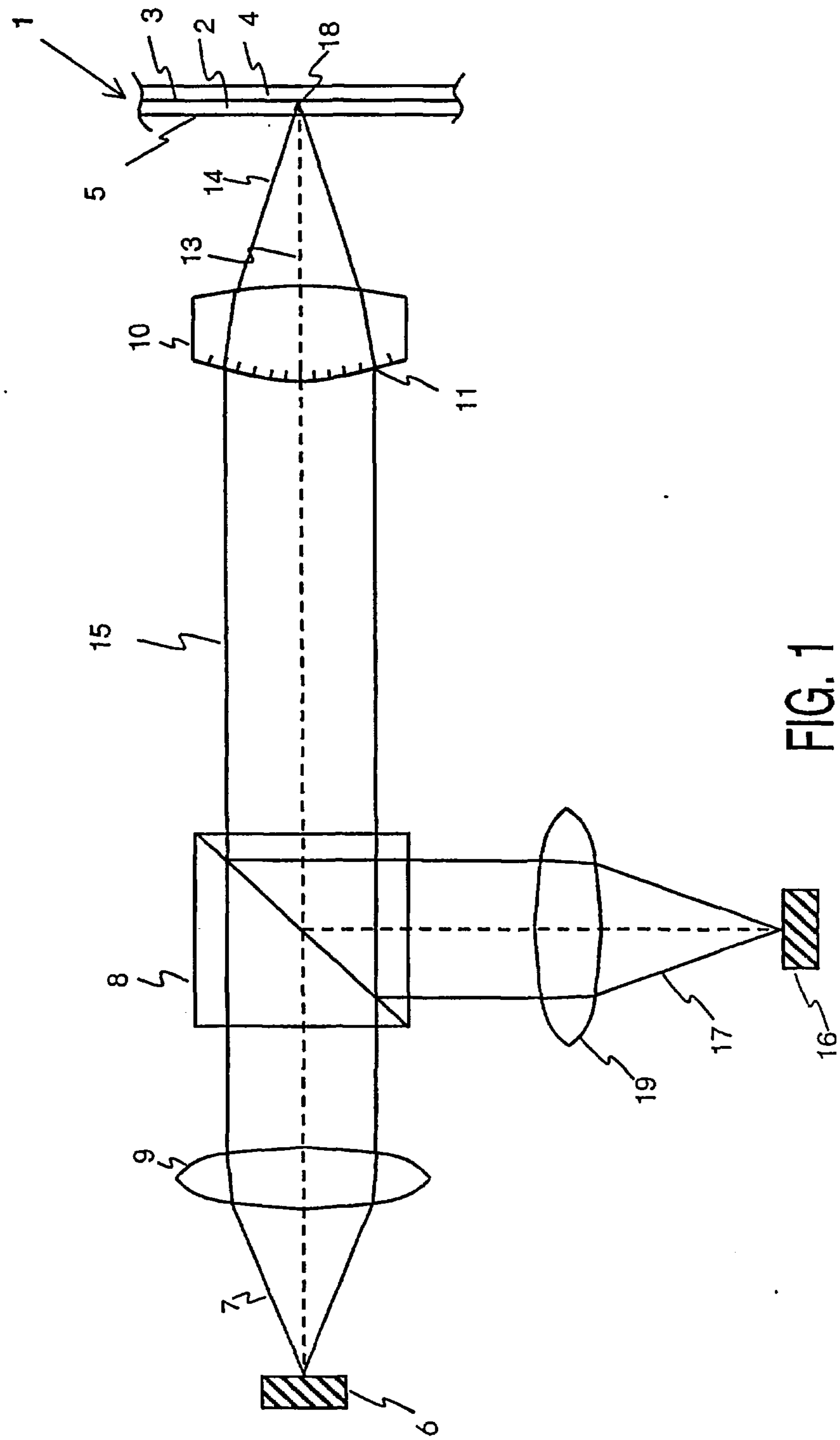


FIG. 1

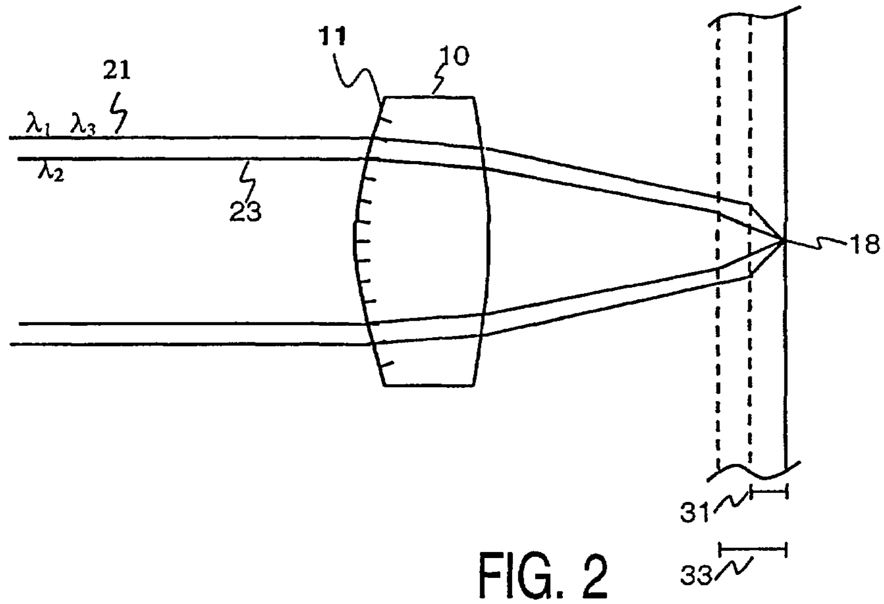


FIG. 2

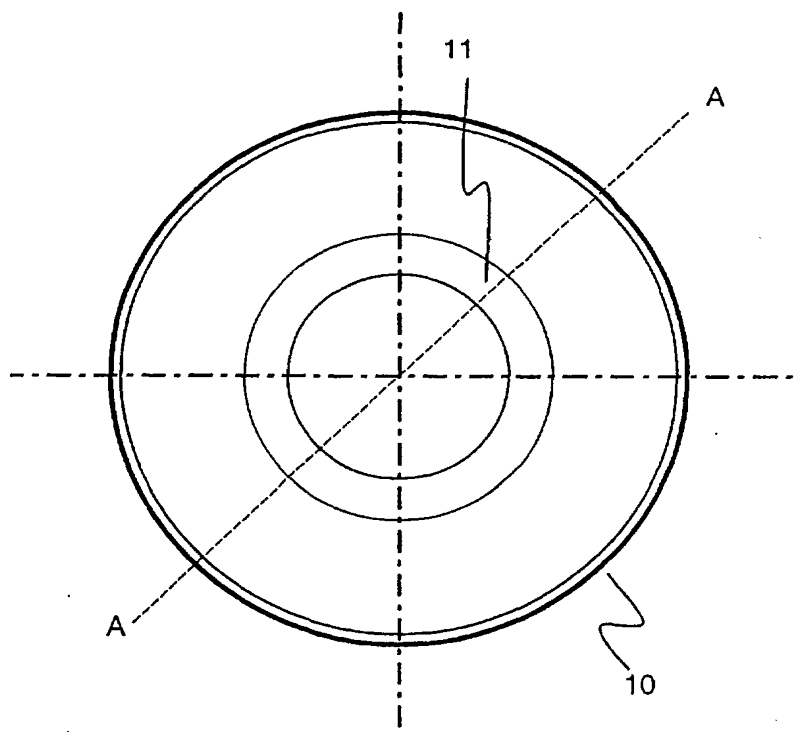


FIG. 3

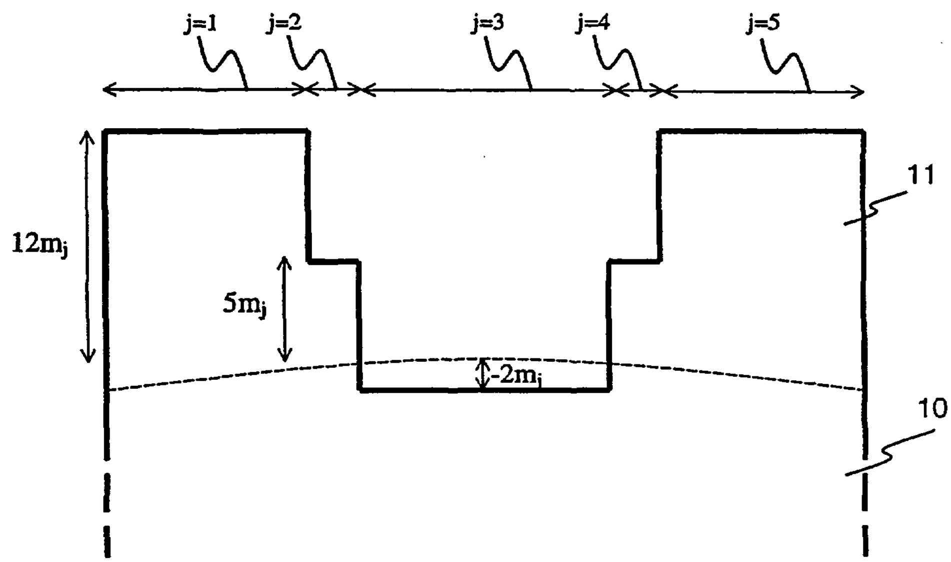


FIG. 4

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IB 02/01063

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G11B7/135 G11B7/125 G02B5/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G11B G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 1 022 731 A (KONISHIROKU PHOTO IND) 26 July 2000 (2000-07-26) abstract paragraph '0212! paragraph '0477! - paragraph '0478!; figures 91-97	1-3,8,9, 12
Y		4
A		5-7,10, 11

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
29 August 2002	06/09/2002

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Annibal, P

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
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